Energy in perspective

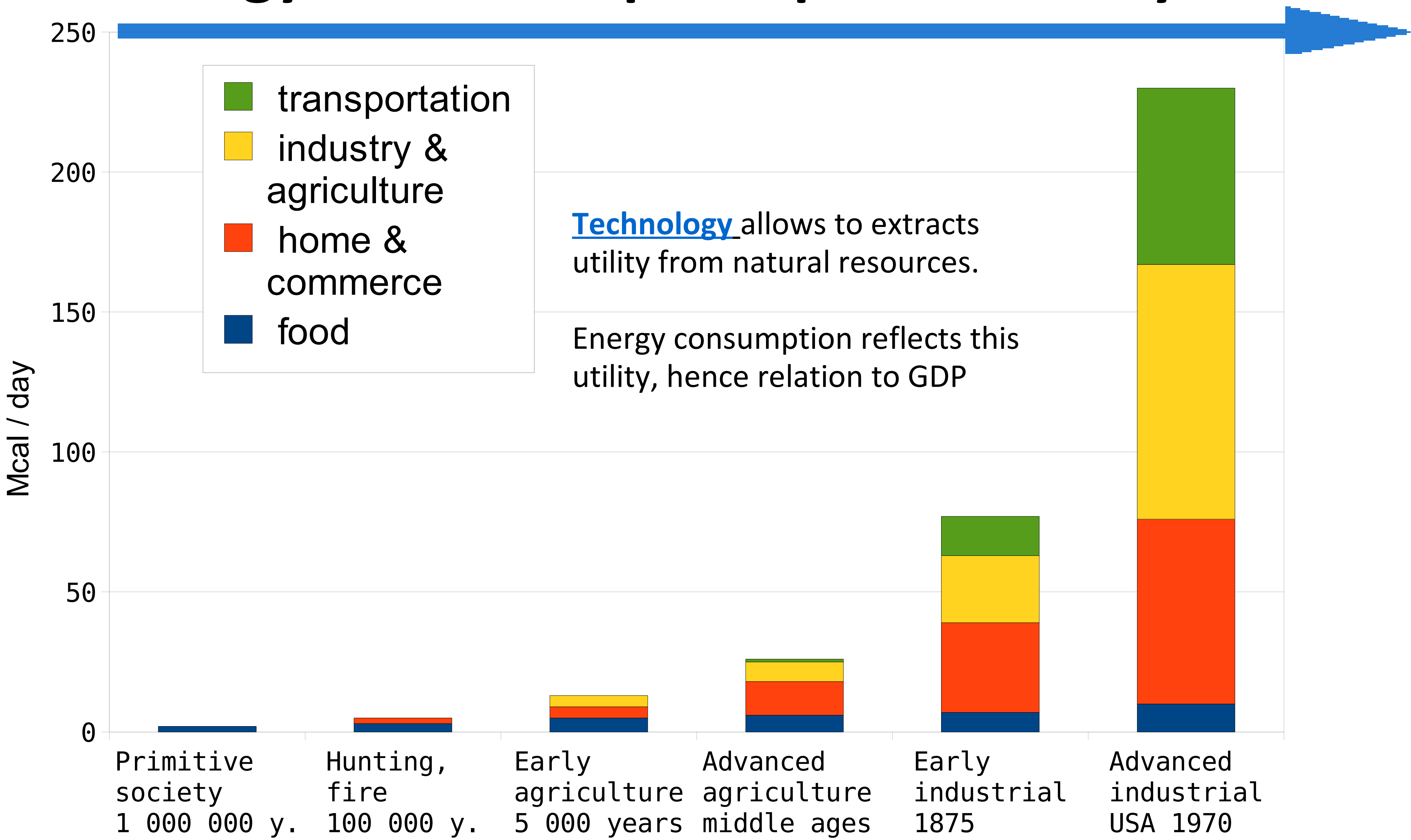
Ondřej Chvála

Outline

History of energy use
Energy consumption and quality of life
Apples to apples comparison of energy resources

Thorium Energy Alliance
Oct 19-20 2009

Energy extraction per capita in history



References:http://www.wou.edu/las/physci/GS361/electricity%20generation/HistoricalPerspectives.htm

Development of human civilization is closely connected to energy consumption

Energy consumption per capita in several stages of development

Mcal / day	Primitive society 1 000 000 y.	Hunting, fire 100 000 y.	Early agriculture 5 000 years	Advanced agriculture middle ages	Early industrial 1875	Advanced industrial USA 1970
food	2	3	5	6	7	10
home & commerce	0	2	4	12	32	66
industry & agriculture	0	0	4	7	24	91
transportation	0	0	0	1	14	63
total Mcal / day / person	**2**	**5**	**13**	**26**	**77**	**230**
total GJ / year / person	3.1	7.6	19.9	39.7	117.7	351.5
total average kW / person	**0.1**	**0.2**	**0.6**	**1.3**	**3.7**	**11.1**

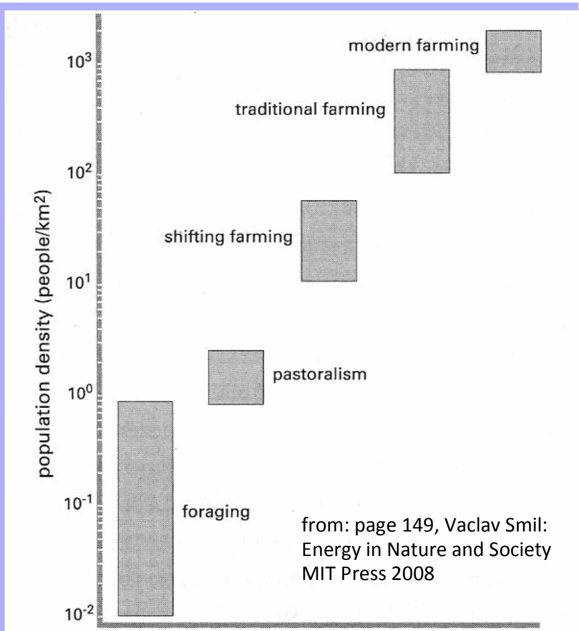
* http://www.wou.edu/las/physci/GS361/electricity%20generation/HistoricalPerspectives.htm

Adapted from: E. Cook, "The Flow of Energy in an Industrial Society" Scientific American, 1971 p. 135.

Total per capita use in technological age is ~100x that of the primitive society
non-SI unit: “Energy slave” (ES) - 8h/day 60 W useful work.
500 energy slaves/capita which heat homes, water, transport people and stuff, drive machines in factories etc.
Can two ES provide a 120W computer? We live in golden times

Most of the energy consumption growth occurs and is expected in developing countries (>3G people)
- rising from early industrial-like poverty
- transfer of heavy manufacturing from developed world

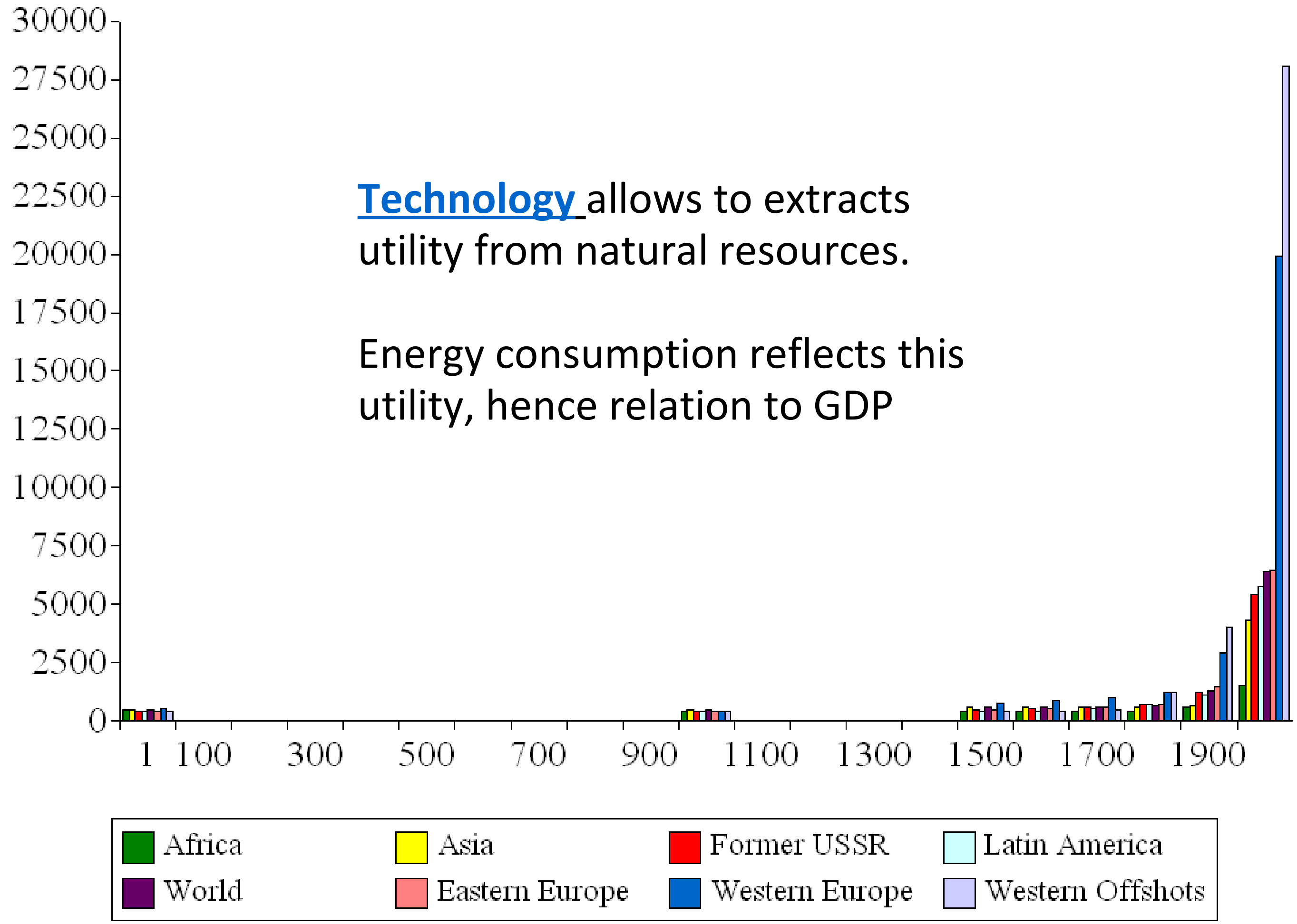
“Carrying capacity” for humans depends on civilization stage and resp. technology (now from Haber-Bosch to satellite controlled farming)



6.1 Ranges of population densities supportable by intensifying modes of food provision.

World GDP/capita [1990 USD]

years: 1, 1000, 1500, 1600, 1700, 1820, 1900, and 2003

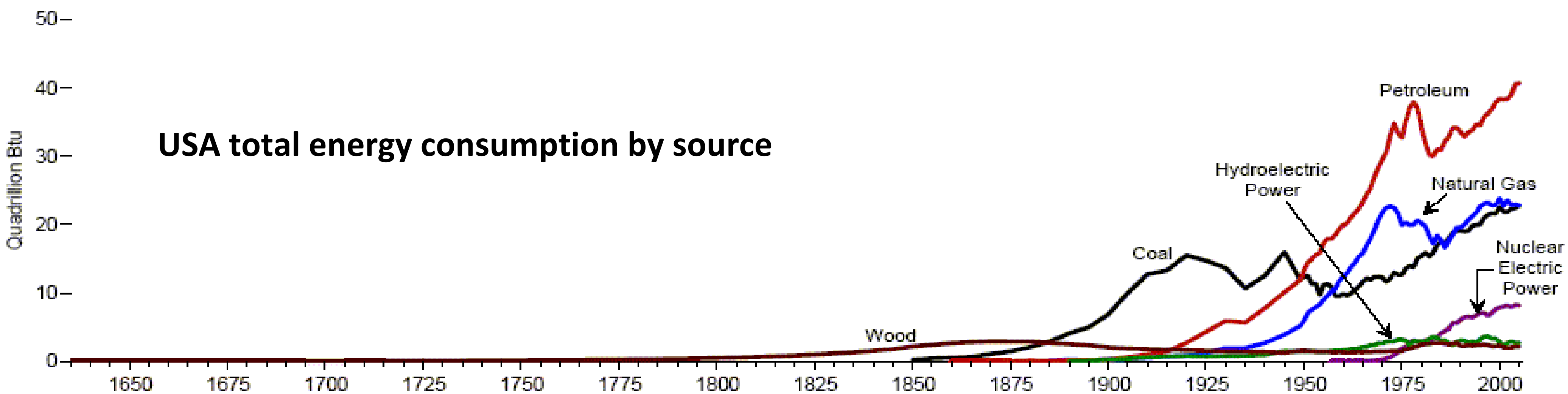


Technology allows to extracts utility from natural resources.

Energy consumption reflects this utility, hence relation to GDP

References:http://en.wikipedia.org/wiki/Gross_domestic_product#Standard_of_living_and_GDP

USA – historic perspective of energy use

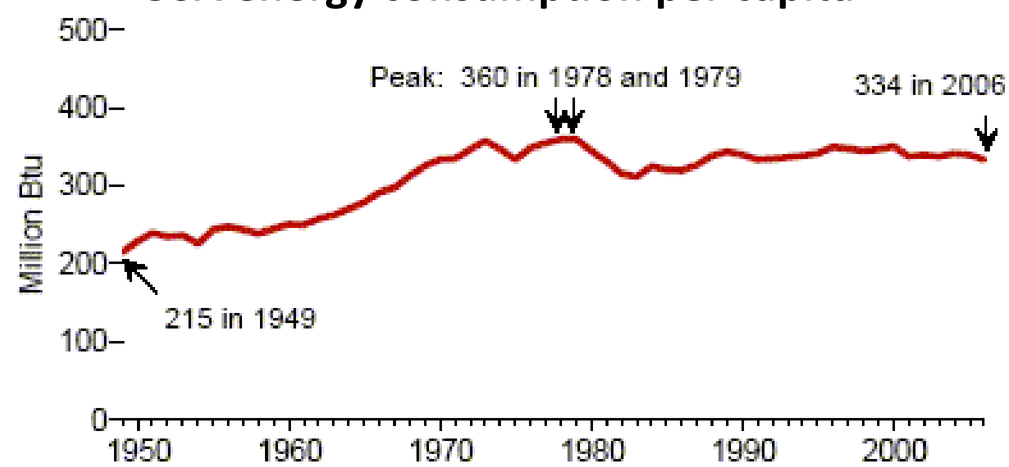


(*) plots from: http://www.eia.doe.gov/emeu/aer/ep/ep_frame.html

Energy consumption per capita is mostly determined by civilization era.
In the technological age, per capita energy consumption grwth stops, however we need to change the energy source away from combustion.

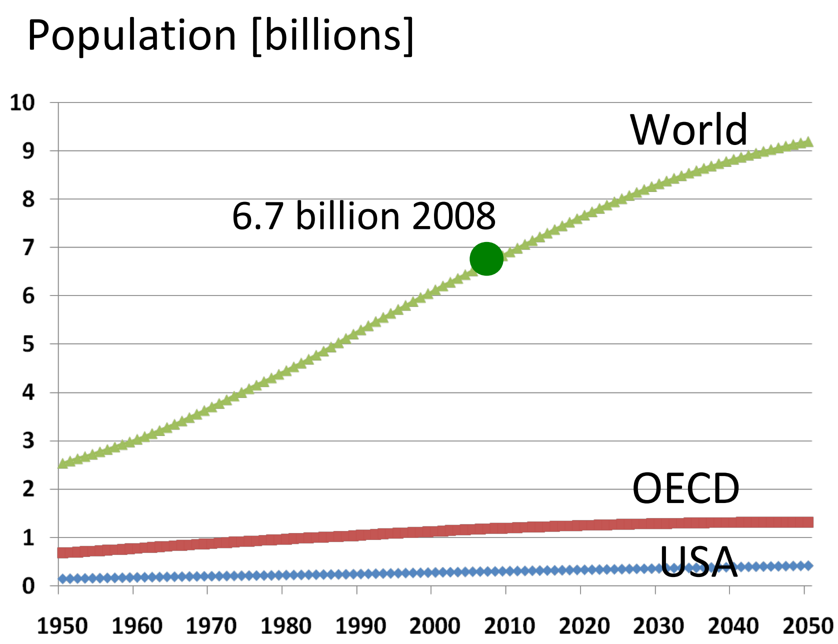
Total energy consumption by humans will rise as billions living in 3rd world countries transit from agriculture and industrial civilizations to the technological age.

USA energy consumption per capita



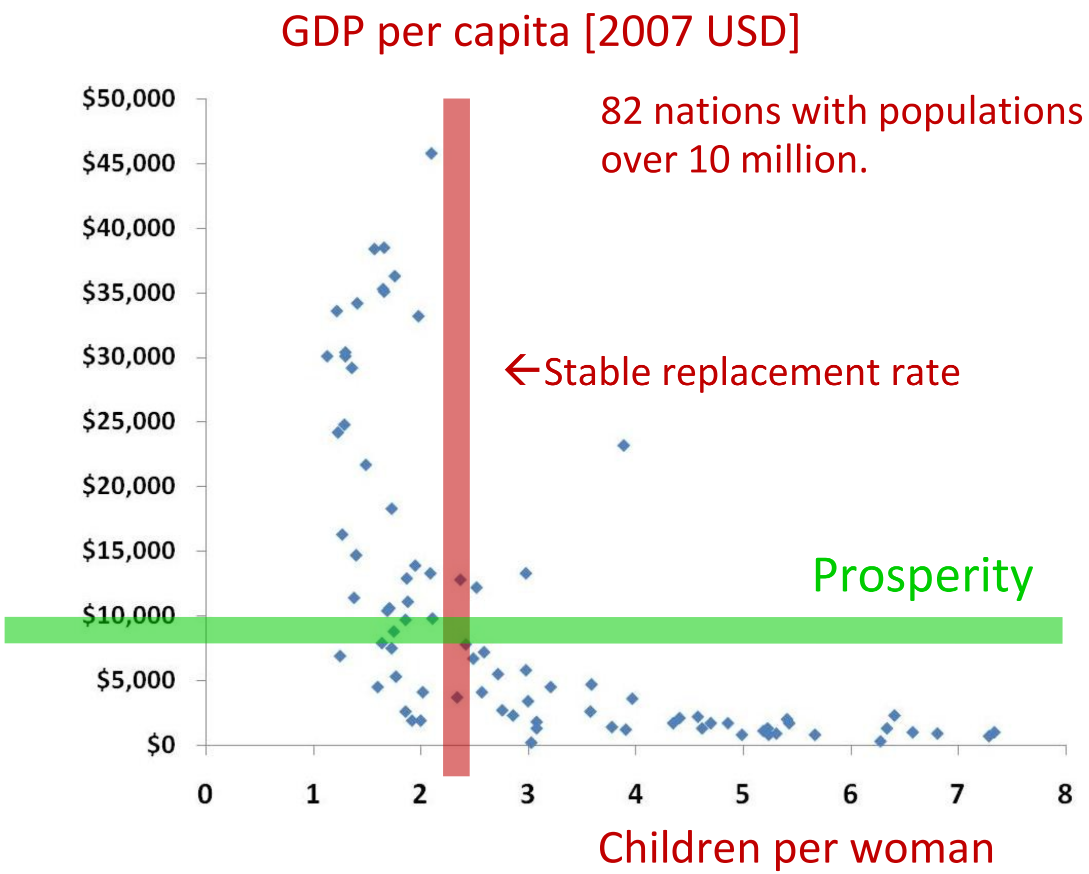
Population

Population is stable in developed countries



References:
http://caliban.sourceoecd.org/vl=1260748/cl=17/nw=1/rpsv/factbook/010101.htm
http://www.oecd.org/dataoecd/13/38/16587241.pdf

Prosperity stabilizes population

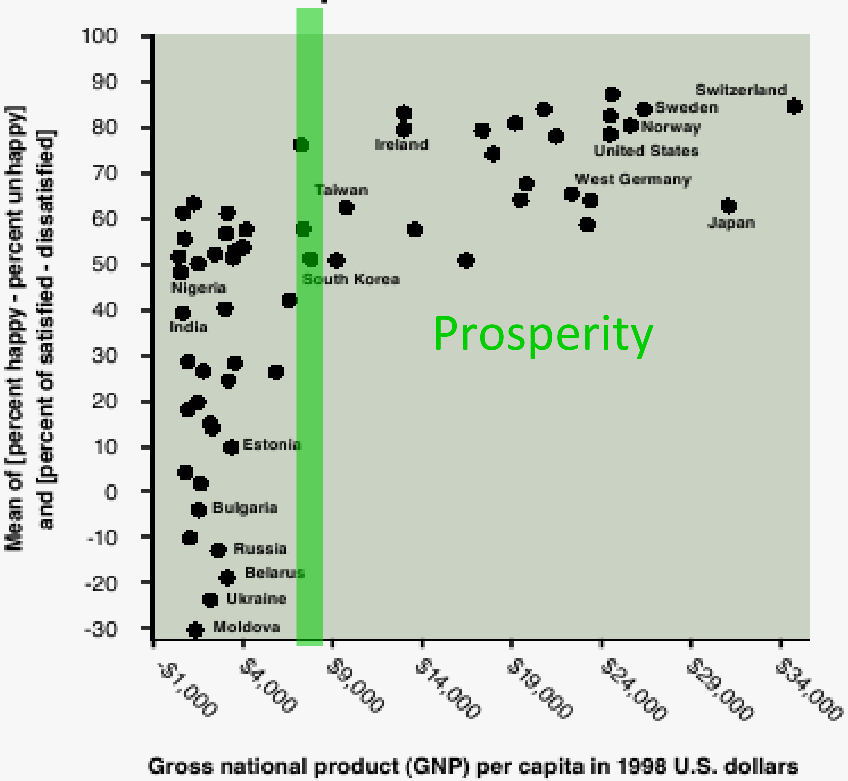


https://www.cia.gov/library/publications/the-world-factbook/docs/rankorderguide.html

From: http://rethinkingnuclearpower.googlepages.com/aimhigh

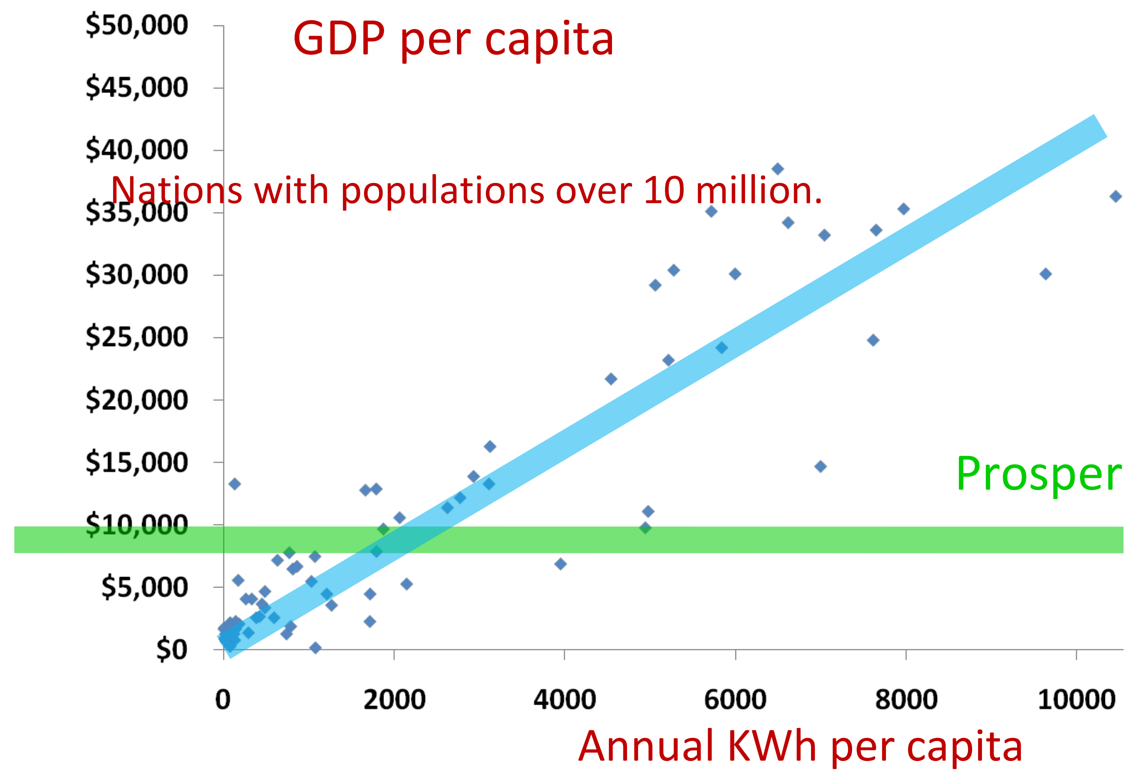
Quality of life and energy consumption I

Figure 1. Subjective well-being by level of economic development



NOTE: The subjective well-being index reflects the average of the percentage in each country who describe themselves as "very happy" or "happy" minus the percentage who describe themselves as "not very happy" or "unhappy"; and the percentage placing themselves in the 7–10 range, minus the percentage placing themselves in the 1–4 range, on a 10-point scale on which 1 indicates that one is strongly dissatisfied with one's life as a whole, and 10 indicates that one is highly satisfied with one's life as a whole.

SOURCE: R. Inglehart, "Globalization and Postmodern Values," Washington Quarterly 23, no. 1 (1999): 215–228. Subjective well-being data from the 1990 and 1996 World Values Surveys. GNP per capita for 1993 data from World Bank, World Development Report, 1995 (New York: Oxford University Press, 1995).

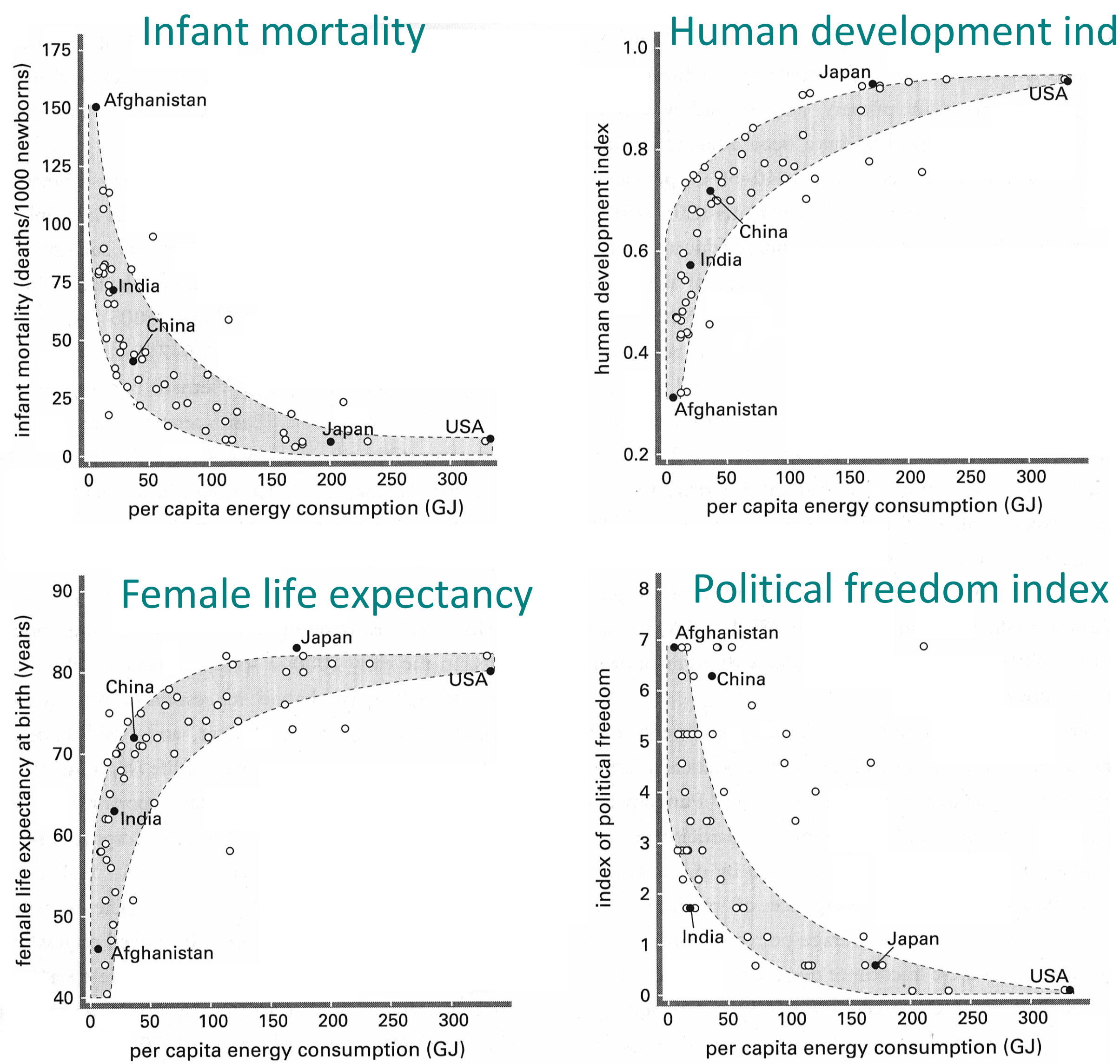


References:
http://rethinkingnuclearpower.googlepages.com/aimhigh
https://www.cia.gov/library/publications/the-world-factbook/rankorder/2042rank.html

$7500 (1998) = $9500 (2007)
http://www.westegg.com/inflation/infl.cgi

Quality of life and energy consumption II

Relationship of several QoL indicators with annual per capita energy consumption



from: Vaclav Smil: Energy in Nature and Society, MIT Press 2008, page 347

About ½ of US total energy consumption seems to be required for decent standard of living.

High energy use
is not a problem
More like a blessing.

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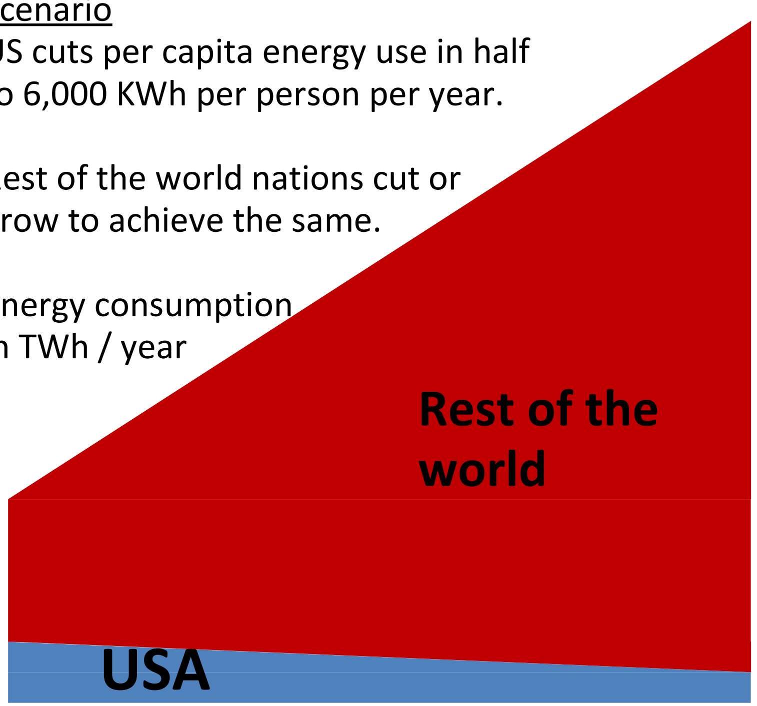
Conservation and efficiency

Energy conservation is economically encouraged (with exceptions such as rental housing)
Lower hanging fruit already collected.
Developing countries need more energy.
Conservation as a solution to energy needs is what starving is to hunger.

<u>Scenario</u>
US cuts per capita energy use in half to 6,000 KWh per person per year.

Rest of the world nations cut or grow to achieve the same.

Energy consumption in TWh / year



Conservation through increasing energy efficiency is inefficient, even futile.

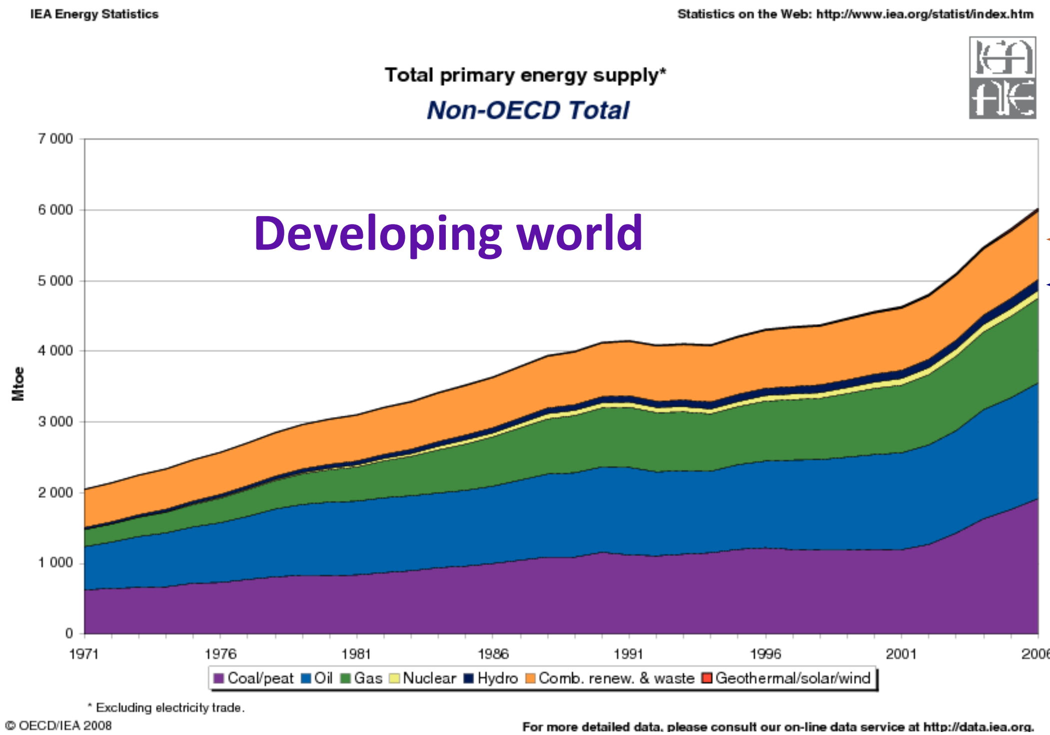
http://en.wikipedia.org/wiki/Jevons_paradox

<u>Jevons paradox</u> <u>(1865)</u>: increase in efficiency of utilizing a resource increases used quantity of the resource due to a) more work is **substituted** by using of the resource; b) cheaper products increased **disposable income** thus buying more.

Both conservation and increased efficiency are obviously positives, which lead to wealth and prosperity by increasing net income and extracting more utility from less of scarce resource, however:

Neither conservation nor efficiency stops global growth of energy use however high energy use as such is not a problem (actually it is benefitial).

Problems with energy production ...

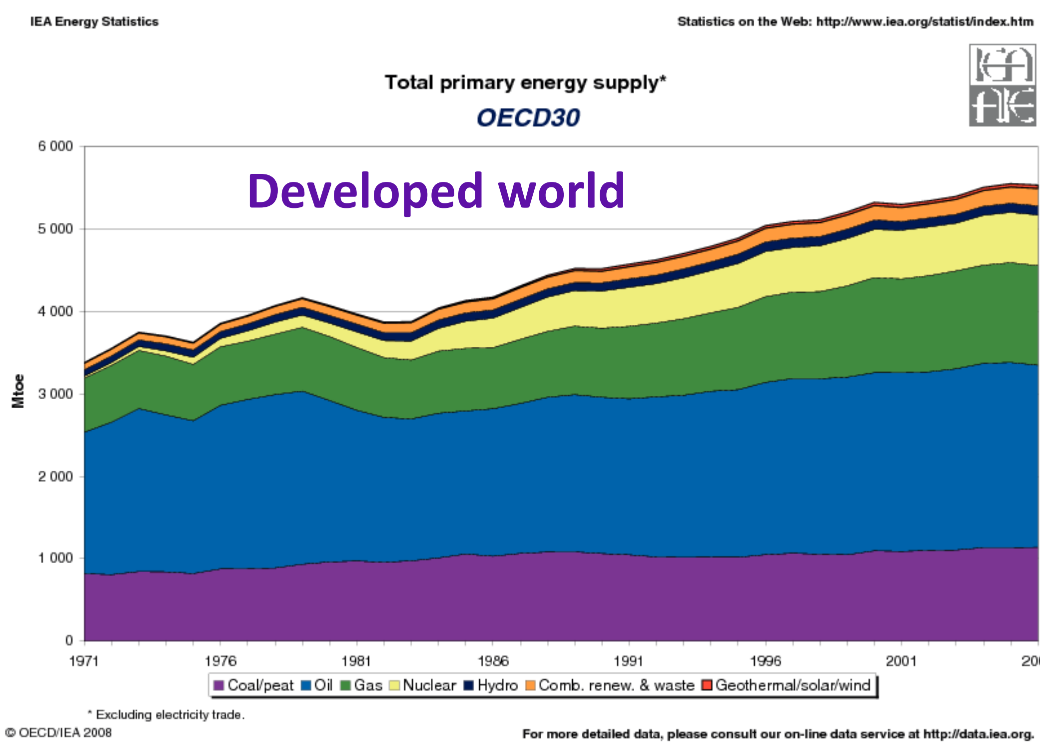


Biomass combustion (wood sticks, trash, animal waste, industrial bio fuels, ...)

Hydro

Fossil fuels

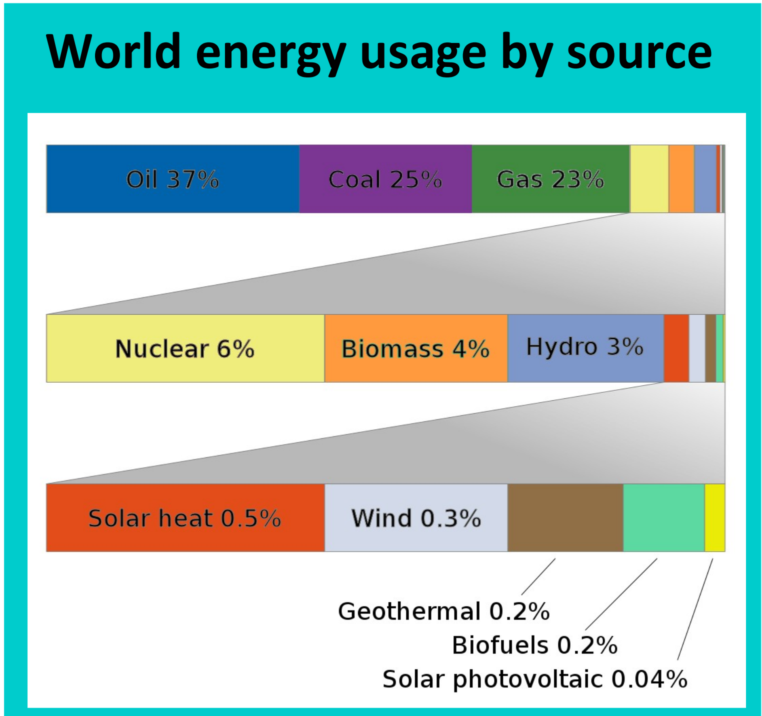
Wind+
Solar+
Geothermal+
Tidal+...



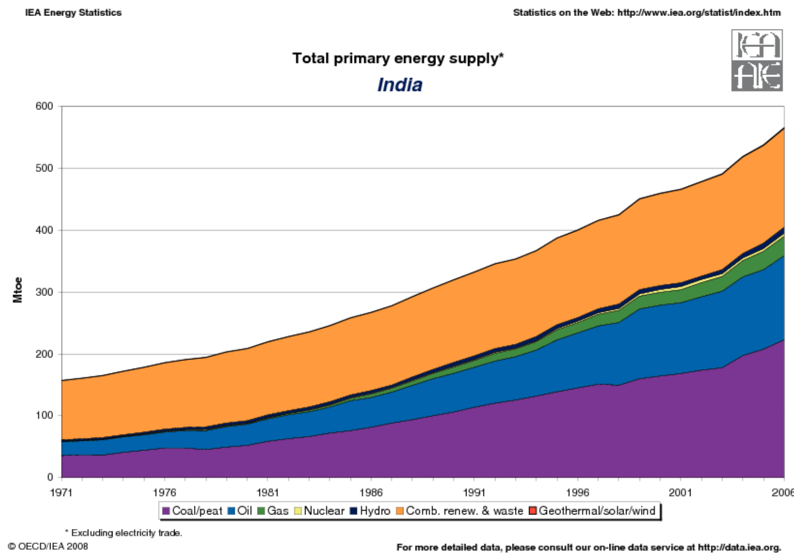
Nuclear

Fossil fuels

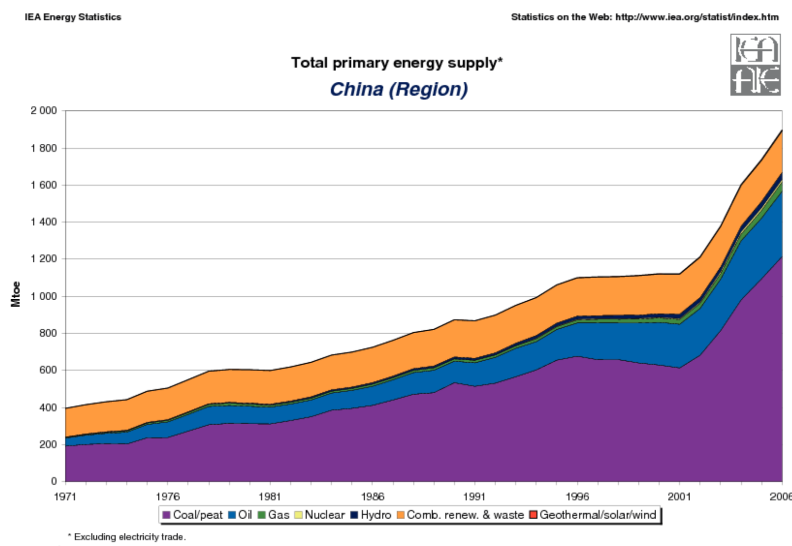
... come by large from combustion of fossils (coal, oil, natural gas)



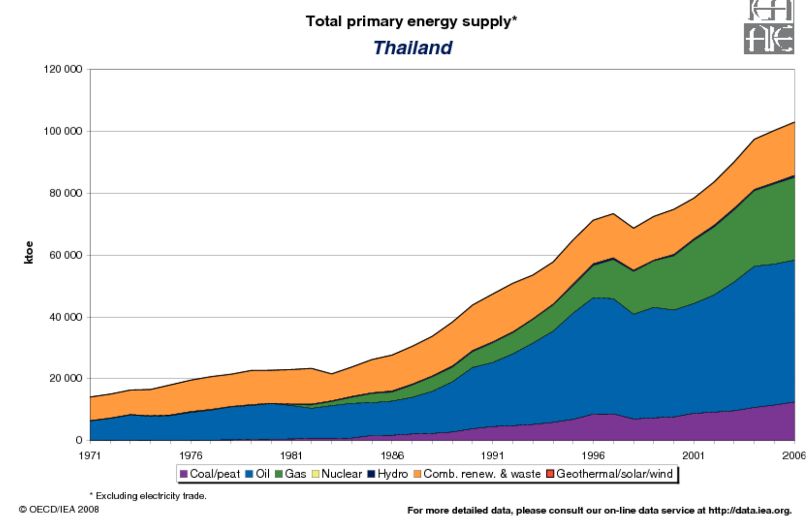
Developing world

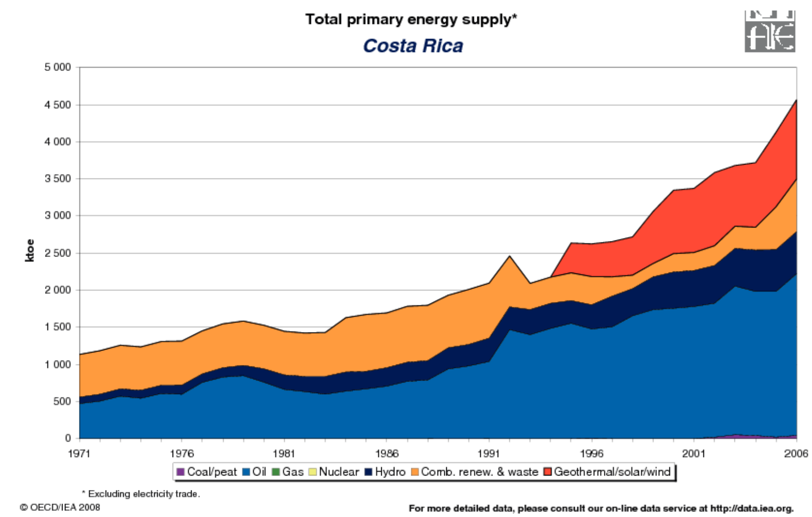


Growth of economy and population fueled By **increased use of fossil fuels**

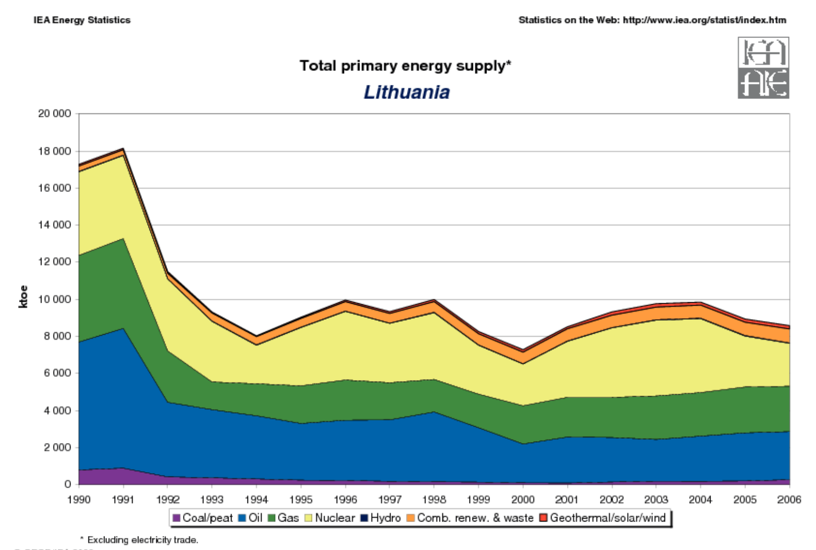


Fossil fuel use growth can be in some cases partially mitigated by use of non-combustion sources.

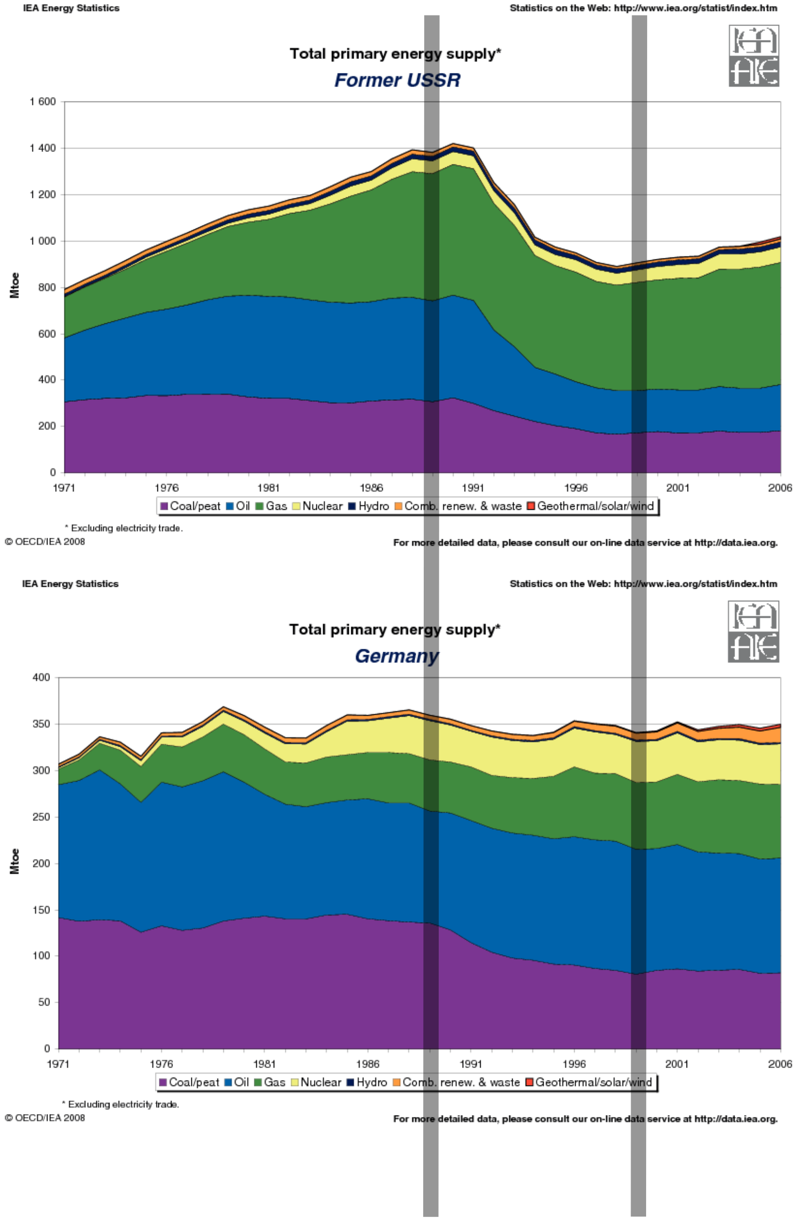


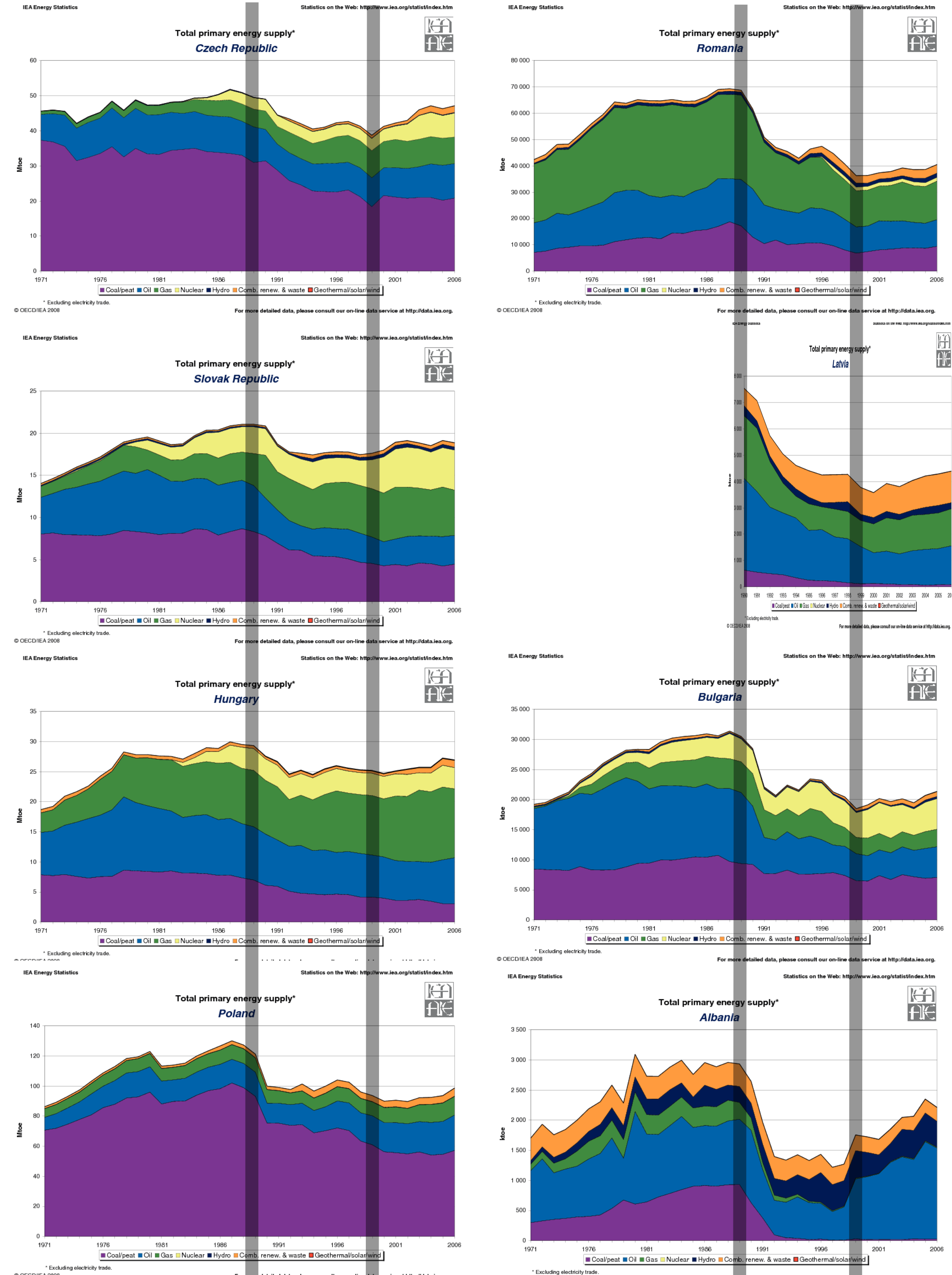


Efficiency gains from replacing soviet system had realized within 5 to 10 years(!!!)



Transition from Soviet economy 1989-1999





1989 1999

1989 1999

1989 1999

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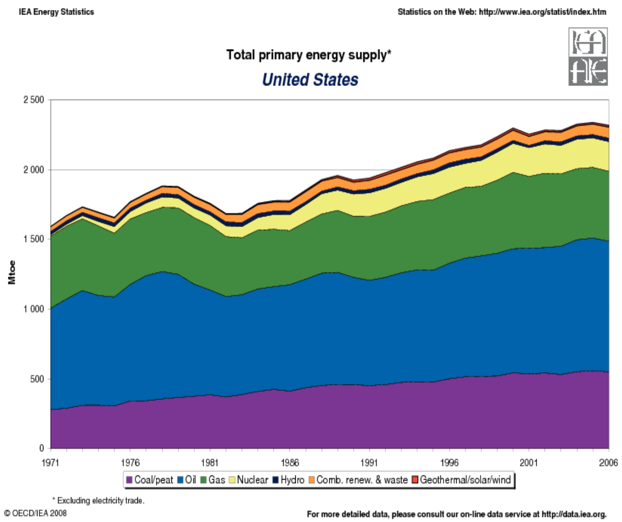
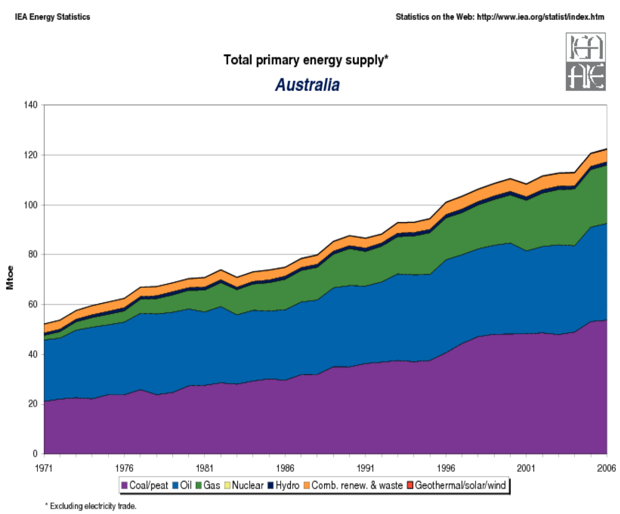
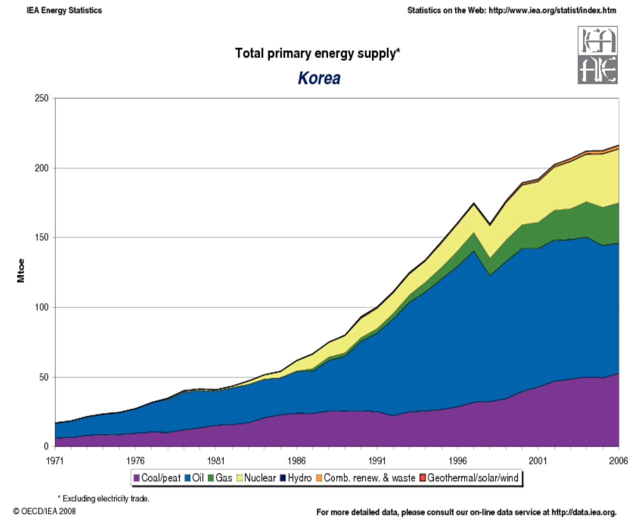
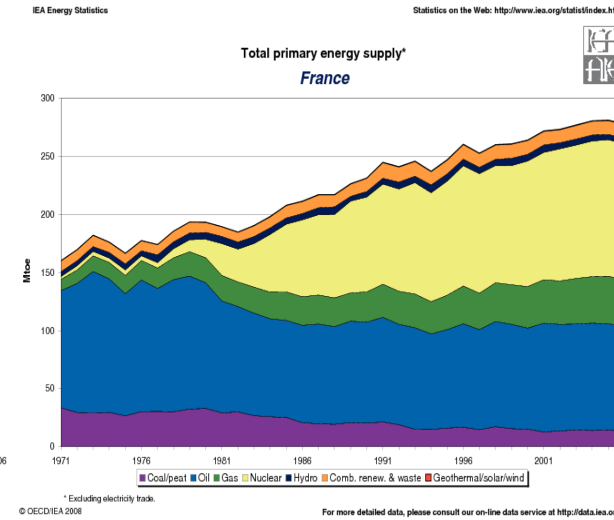
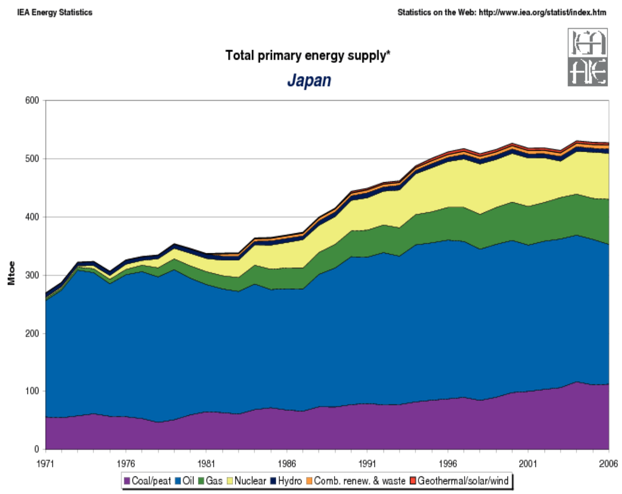
Developed world

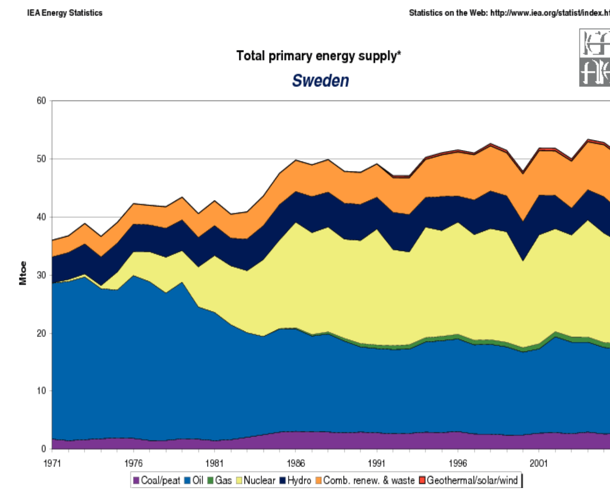


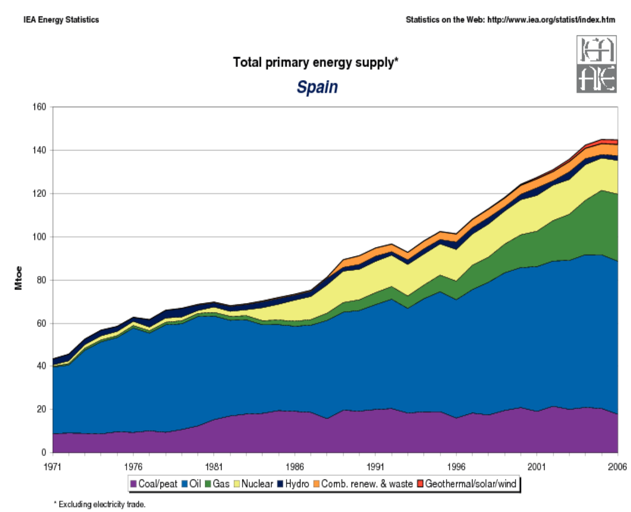


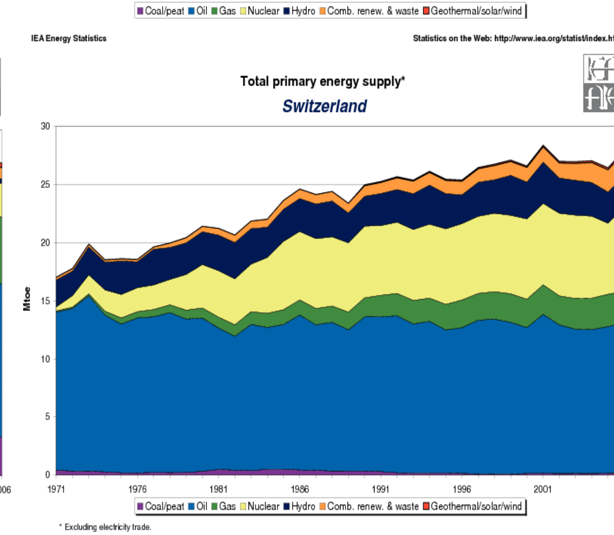












Problems with fossil energy production

Price, Availability, Strategic dependence

"We're paying $700 billion a year for foreign oil" T. Boone Pickens

http://www.usatoday.com/money/industries/energy/2008-07-08-t-boone-pickens-plan-wind-energy_N.htm

Oil: Proved reserves	at end 2007 Thousand million barrels	Share of total	R/P ratio
TOTAL WORLD	1237.9	100.0%	41.6
of which: European Union	6.8	0.5%	7.8
OECD	88.3	7.1%	12.6
OPEC	934.7	75.5%	72.7
Former Soviet Union	128.1	10.4%	27.4
Canadian Oil Sands	152.2		
Proved reserves and oil sands	1390.1		

Natural gas: Proved reserves	at end 2007 Trillion cubic metres	Share of total	R/P ratio
TOTAL WORLD	177.36	100.0%	60.3
of which: European Union	2.84	1.6%	14.8
OECD	15.77	8.9%	14.4
Former Soviet Union	53.53	30.2%	67.7

Coal: Proved reserves at end 2007 Million tonnes	Total	Share of Total	R/P ratio
TOTAL WORLD	847488	100.0%	133
of which: European Union	**29570**	3.5%	50
OECD	**356910**	42.1%	168
Former Soviet Union	**225995**	26.7%	463
Other EMEs	**264583**	31.2%	70

Source of reserves data: Survey of Energy Resources 2007, World Energy Council.

BP: Statistical Review of World Energy 2008

http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2008/STAGING/local_assets/downloads/spreadsheets/statistical_review_full_report_workbook_2008.xls

Ratio of **Reserves to Production** gives years of supply at current rate of consumption

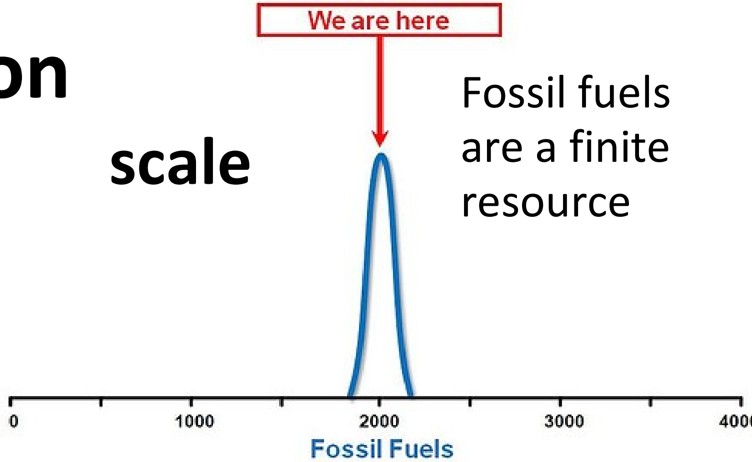
Oil: 42 yR/P
37 % total energy use

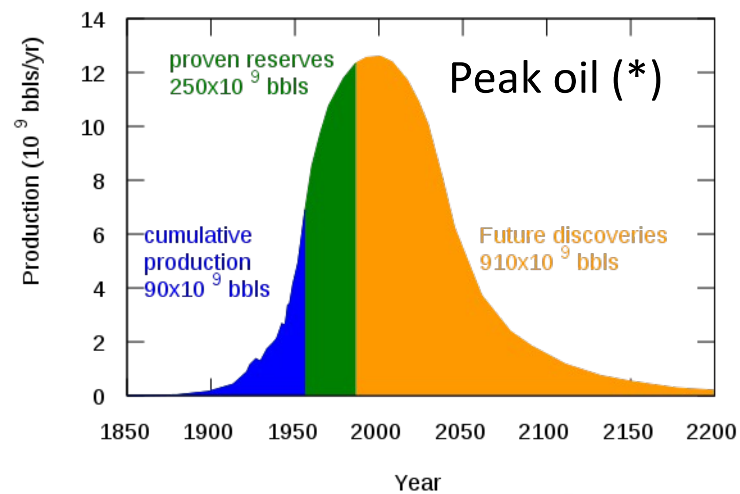
Natgas: 60 yR/P
23 % use
"Abundant"???

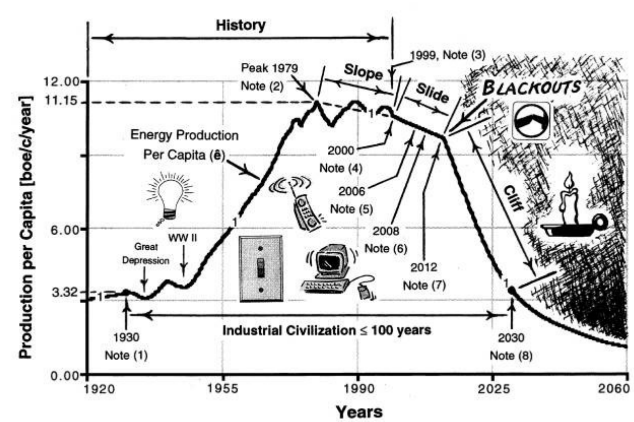
Coal: 133 y R/P
USDoE Secretary Dr. Chu's
"worst nightmare"
Needs to be eliminated by 2030
[J. Hansen et al.]
http://www.columbia.edu/~jeh1

scale

Fossil fuels are a finite resource







(*) for Peak Oil see recent overview Pedro de Almeida, Pedro D. Silva, The peak of oil production--Timings and market recognition, Energy Policy, Volume 37, Issue 4, April 2009, Pages 1267-1276, ISSN 0301-4215, DOI: 10.1016/j.enpol.2008.11.016. (http://www.sciencedirect.com/science/article/B6V2W-4VC744G-2/2/4090d8bfe324ad1abf44166f357a69f9)

Fossils: necessary input for chemical industry (plastics, drugs, fertilizers)

Pollution, Associated risks, Sustainability

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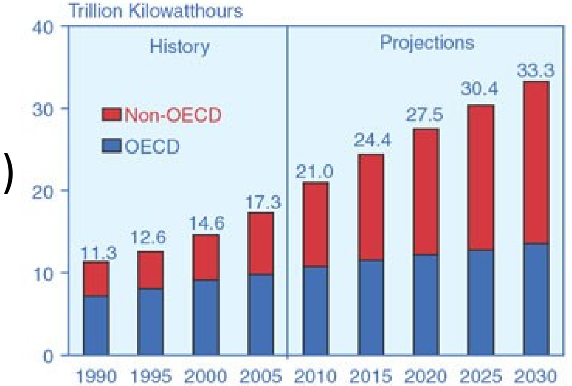
Electricity – flexible energy

Electricity – the most versatile energy, can be very efficiently transformed to other forms (heating, colling, motion;powering factories, lights, computers …)

Figure 53. World Net Electric Power Generation, 1990-2030



Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2005* (June-October 2007), web site www.eia.doe.gov/iea. **Projections:** EIA, System for the Analysis of Global Energy Markets/Global Electricity Module (2008).

Electricity consumption is rising

Developed countries – electrify transportation

Developing – electricity essential to alleviate poverty

Agriculture: N fixation (Haber-Bosh process) 100M t/year of fertilizers

Currently natgas cheaper (3-5% of world natgas consumption)

http://en.wikipedia.org/wiki/Haber_process

Synthetic fuels: "Los Alamos National Laboratory has developed a low-risk, transformational concept, called Green Freedom™, for large-scale production of carbon-neutral, sulfur-free fuels and organic chemicals from air and water." Operating costs $1.40/gal of synthetic gasoline.
Competitive with gas at pump costs $4.60/gal (high investment risk), $3.40 with some improvements

http://www.lanl.gov/news/index.php/fuseaction/home.story/story_id/12554
http://www.lanl.gov/news/newsbulletin/pdf/Green_Freedom_Overview.pdf

Landfills → plasma arc melting

Recycles everything but rad-waste

Atomize waste → syngas (CO+H) → chem. feedstock, electricity
→ melted slag – metals separated, partitioned, recycled;
the rest (silicates) → tiles, roadbeds, rock-wool 10x cheaper

1999 Hitachi Metals pilot plant, 2002 car recycling plant
now: 7 plants world wide, 7 under construction
Florida: 910 t waste/day

http://science.howstuffworks.com/plasma-converter.htm
http://en.wikipedia.org/wiki/Plasma_arc_gasification

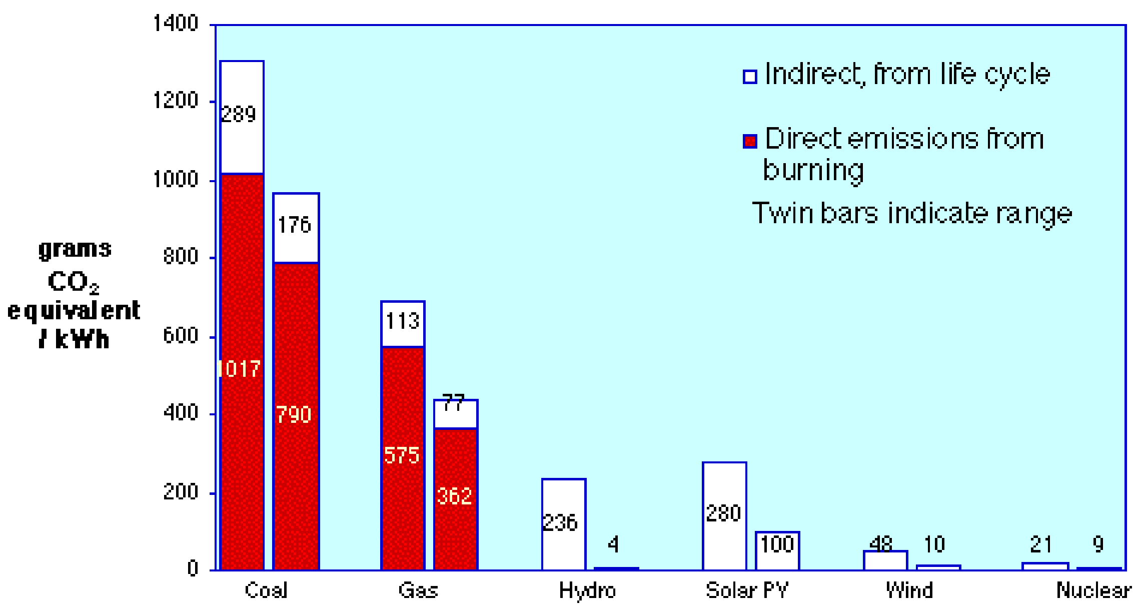
Emissions

Climate Change – emissions of Green-House Gases (GHG) from human activities are the major contributor

40% of US CO_2 emission – electricity generation, coal contributes >80%

Concerning **climate change**, see this article by J. Hansen from NASA GISS:
http://www.columbia.edu/~jeh1/2008/AGUBjerknes_20081217.pdf

Greenhouse Gas Emissions from Electricity Production



Source: IAEA 2000

Life-Cycle analysis of emissions shows:

- **Coal is particularly bad**
- Other fossil fuels are not much better (order: coal, oil, gas)
- Order of magnitude improvements possible only with non-combustion sources

Other combustion pollutants

SO_2, NO_X – acid rain, smog
particulate matter (PM)

arsenic, mercury, cadmium, uranium, thorium, … →

toxic fossil waste **"exempted from federal hazardous waste regulations"** [EPA]
http://www.epa.gov/osw/nonhaz/industrial/special/fossil/index.htm
http://www.commondreams.org/headline/2009/01/07-2

PM emissions (soot) from coal combustion alone are responsible for 24 000 annual deaths in the US.
http://www.catf.us/publications/view/24

What is in coal?

	Ppm
Ag	5 – 10
Au	0,2 – 0,5
As	8000
B	8600
Be	2800
Bi	200
Cd	80
Co	2000
Cr	1200
Cs	4
Cu	4000
Ga	6000
Ge	90000
Hg	50
I	950
In	2
La	31
Li	960
Mo	2000
Mn	22000
Nb	2
Ni	16000
Pb	1000
Pt	0,7
Rb	33
Sb	3000
Sc	400
Sn	6000
Ta	0,1
Ti	20000
Tl	25
U	600
V	11000
Y	800
Zn	10000

"The energy content of nuclear fuel released in coal combustion is more than that of the coal consumed!"
http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html

More on coal:
http://pubs.usgs.gov/fs/1997/fs163-97/FS-163-97.html
http://energy.er.usgs.gov/products/databases/CoalQual/intro.htm
http://www.savethecleanairact.org/factsheet.html

ExternE - Externalities of Energy. A Research Project of the European Commission

Externalities

External costs can be measured: comprehensive study of polluting emissions and their impacts.
See http://www.externe.info for details.

External costs for electricity production in the EU (in EUR-cent per kWh)

Country	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
AUT				1-3		2-3	0.1		
BE	4-15			1-2	0.5				
DE	3-6		5-8	1-2	0.2	3		0.6	0.05
DK	4-7			2-3		1			0.1
ES	5-8			1-2		3-5*			0.2
FI	2-4	2-5				1			
FR	7-10		8-11	2-4	0.3	1	1		
GR	5-8		3-5	1		0-0.8	1		0.25
IE	6-8	3-4							
IT			3-6	2-3			0.3		
NL	3-4			1-2	0.7	0.5			
NO				1-2		0.2	0.2		0-0.25
PT	4-7			1-2		1-2	0.03		
SE	2-4					0.3	0-0.7		
UK	4-7		3-5	1-2	0.25	1			0.15

* : biomass co-fired with lignites
** : sub-total of quantifiable externalities
(such as global warming, public health, occupational health, material damage)

Average [USD cents]	8.6	4.6	6.6	2.0		1.8				combustion
					0.5		0.6	0.8	0.2	non-combustion

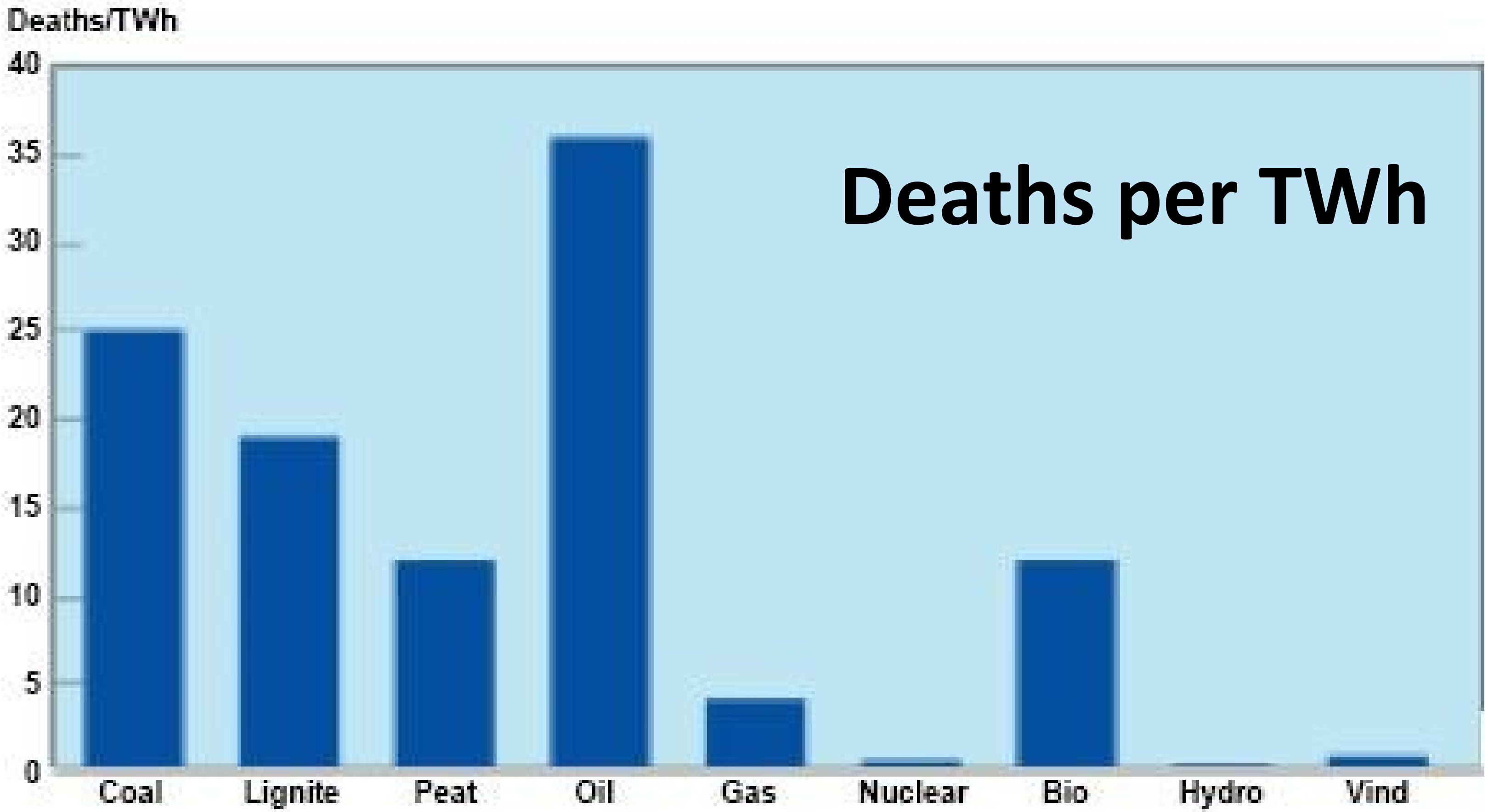
Including the external price would <u>double</u> production cost

<u>Solutions</u> - issue dependent
CFC ban
SO2, NOx – mandatory pollution control
CO2 – carbon tax

<u>Nuclear is the only</u> energy resource which pays for externalities
→ spent fuel fund
→ D&D fund

Every industrial scale activity is somewhat unsafe

Risks can be measured



Non-combustion sources of energy are much safer!

References:

http://www.iaea.org/Publications/Magazines/Bulletin/Bull411/41104991518.pdf
http://www.eurekalert.org/images/release_graphics/pdf/EH2.pdf
http://nextbigfuture.com/2008/03/deaths-per-twh-for-all-energy-sources.html

"In the mid-1990s the mortally rate was actually 0.4 per TWh. The worldwide mortality rate dropped more than half to 0.15 deaths per TWh by the end of 2000."
http://www.wind-works.org/articles/BreathLife.html

http://www.caithnesswindfarms.co.uk/accidents.pdf
http://nuclearpoweryesplease.org/pub/Economic%20Analysis%20of%20Various%20Options%20of%20Electricity%20Generation.pdf
http://www3.interscience.wiley.com/journal/119120107/abstract
http://depletedcranium.com/?p=1738

Cost is essential

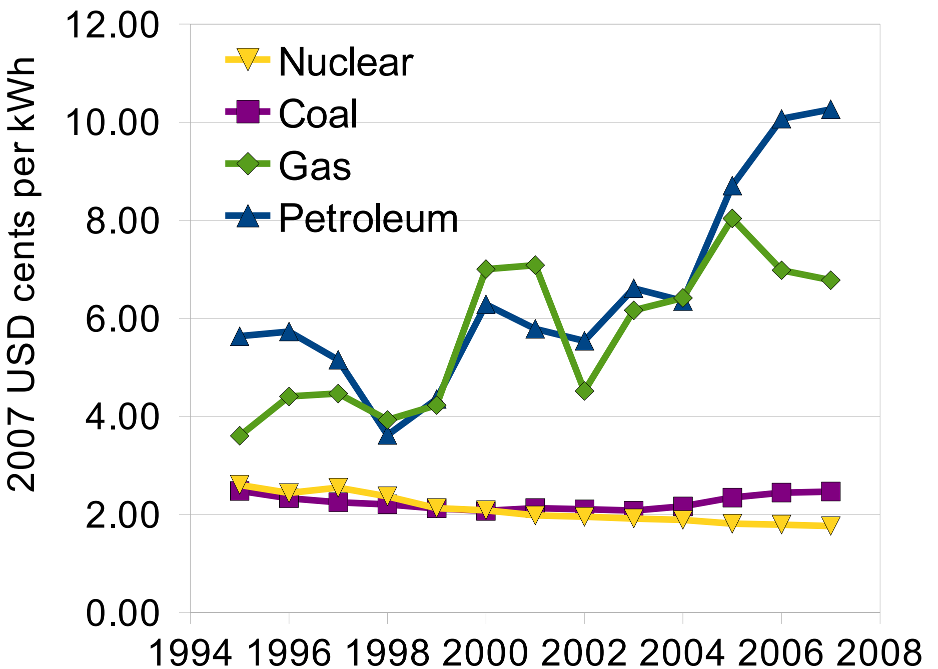
Price is crucial, esp. for developing world

Cheap Clean energy – otherwise dirty cheap coal

http://theenergycollective.com/TheEnergyCollective/37028

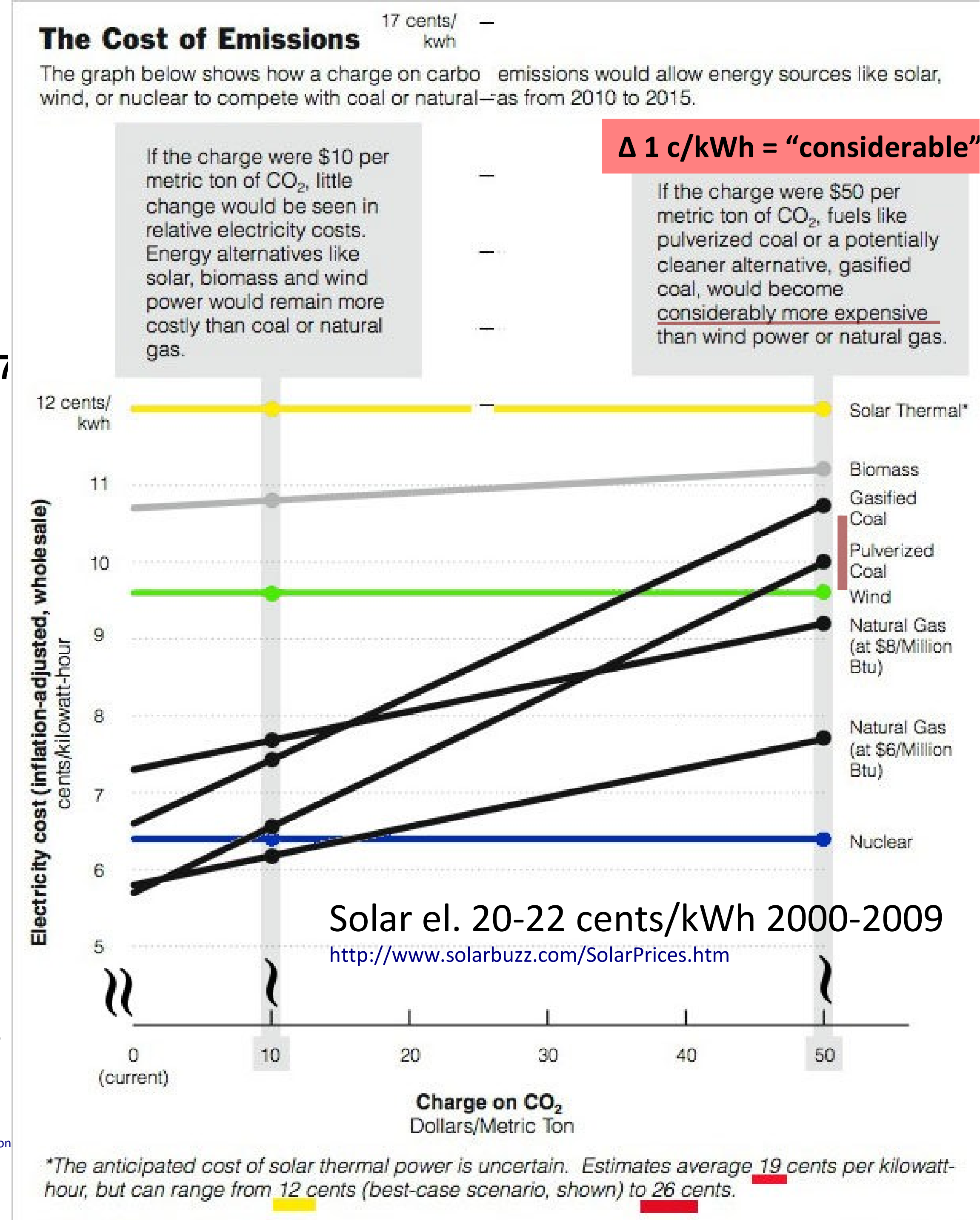
http://www.youtube.com/watch?v=71kckb8hhOQ

U.S. Electricity Total Production Costs 1995 - 2007



Annual average U.S. electricity production, operations and maintenance (O&M), and fuel costs from 1995 to 2007 for nuclear, coal, gas and oil.

http://www.nei.org/resourcesandstats/documentlibrary/reliableandaffordableenergy/graphicsandcharts/uselectricityproductioncostsandcompon



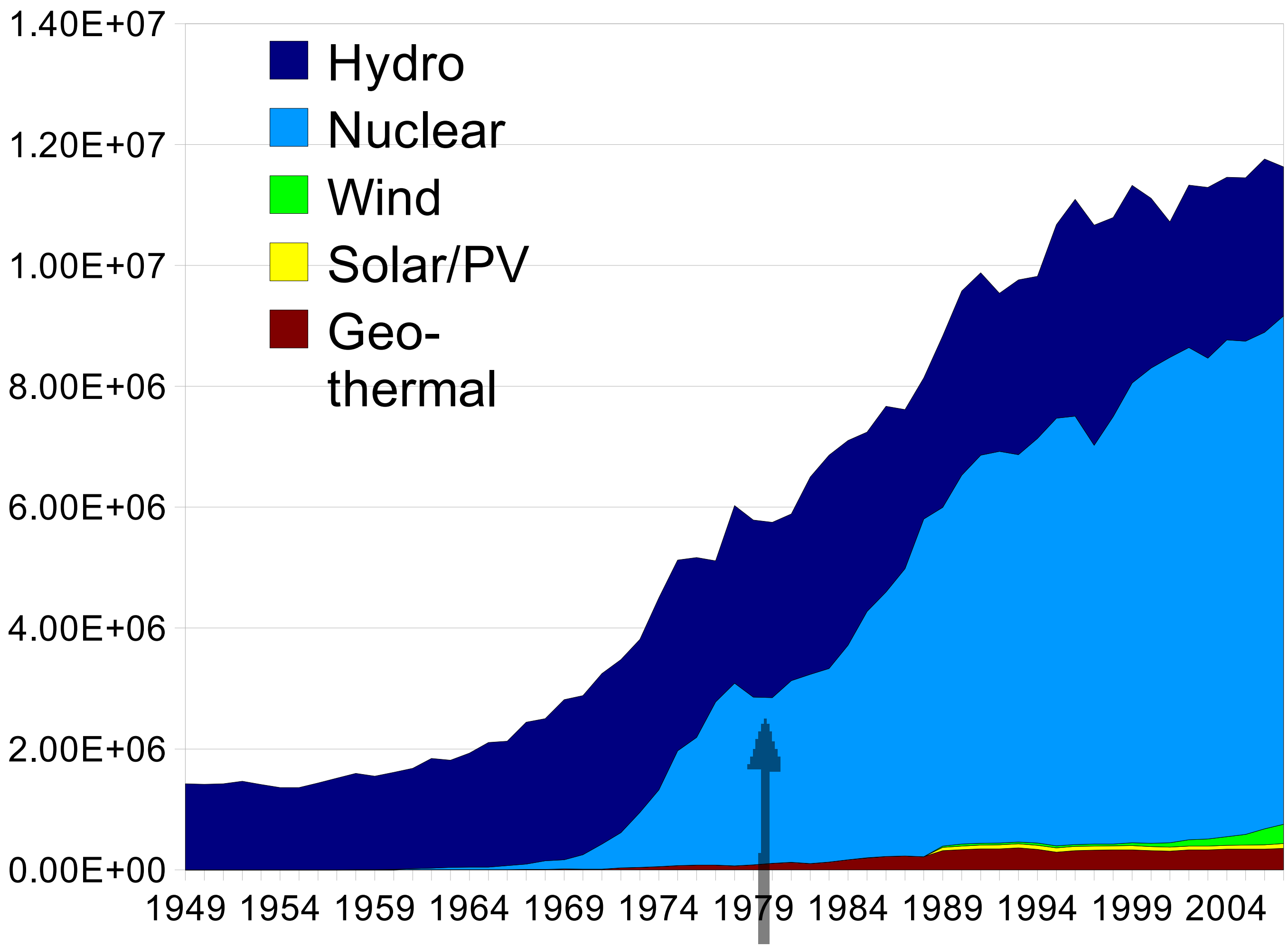
http://www.nytimes.com/2007/11/07/business/businessspecial3/07carbon.html

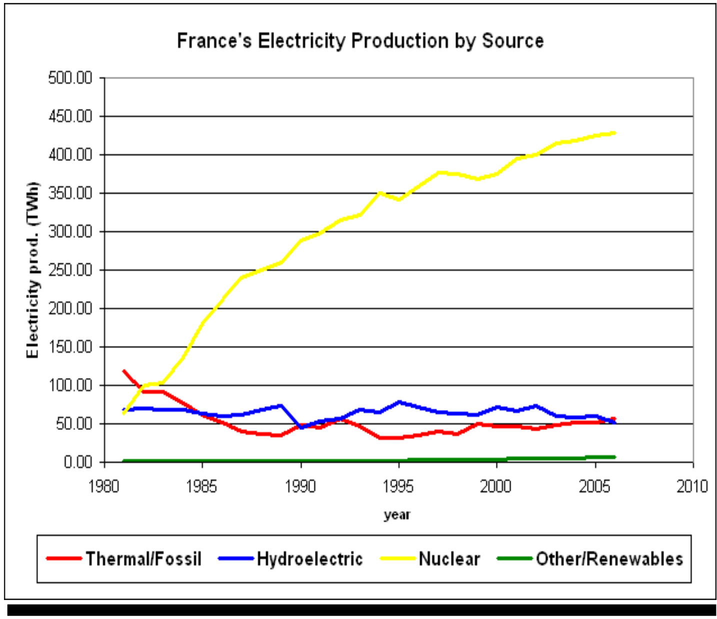
Real Clean energy

Note: France after the 1973 decision went to 80% electricity in about 25 years; closed the last coal mine in 2004

Links:
http://news.bbc.co.uk/2/hi/europe/3651881.stm
http://en.wikipedia.org/wiki/Nuclear_power_in_France

U.S. non combustion energy sources (Billion Btu)





US Energy Information Agency Table 1.3, The Annual Energy Review, 2007
http://www.eia.doe.gov/emeu/aer/overview.html

NB2: **USA EIA 1972** prediction
who killed US nuclear power?
http://www.google.com/search?hl=en&q=smoking%2Bgun+site%3Aat
http://www.21stcenturysciencetech.com/2006_articles/spring%20200
http://atomicinsights.blogspot.com/2009/04/anti-nuclear-effectively-means-pr

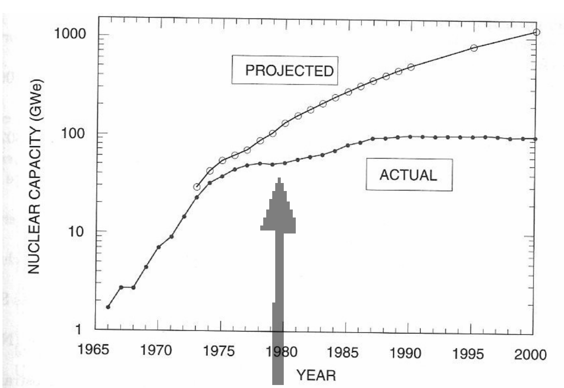


Fig. 2.5. Comparison of U.S. nuclear capacity, projected in 1972 and actual.

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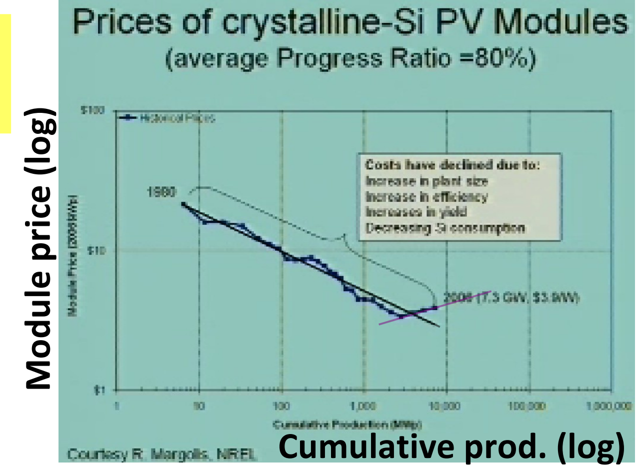
Solar energies

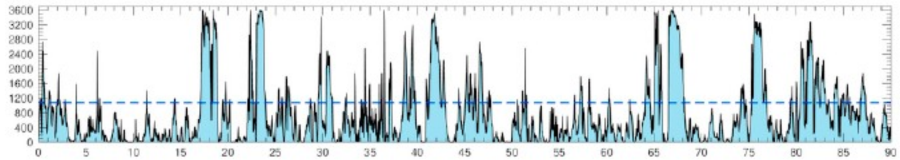
Unrealistic with demonstrated technologies
Invest into R&D (nanotechnology?)



Wind, solar, biomass – the best known (oldest) energy resources
Excellent in particular applications, from calculators to satellites, off grid locations, water pumping, bio-waste use, passive solar heating, ...

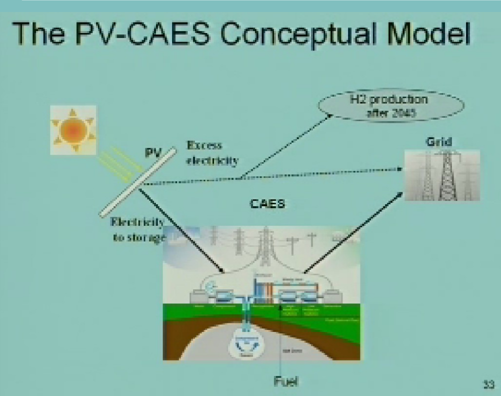
Thousands of years spent developing them. Major problems facing large scale deployment still unresolved: **intermittency** → need for energy storage, **low power density** → large demands on raw material (cost) and covered land area (cost, env. impacts)
http://www.washingtonpost.com/wp-dyn/content/article/2009/04/15/AR2009041503622.html
http://phe.rockefeller.edu/docs/HeresiesFinal.pdf
http://www.msnbc.msn.com/id/30240000/

Mass production issues: toxic pollution from PV panel production (SiCl4) in China
http://www.treehugger.com/files/2008/03/solar_pollution_china.php
http://www.washingtonpost.com/wp-dyn/content/article/2008/03/08/AR20080308



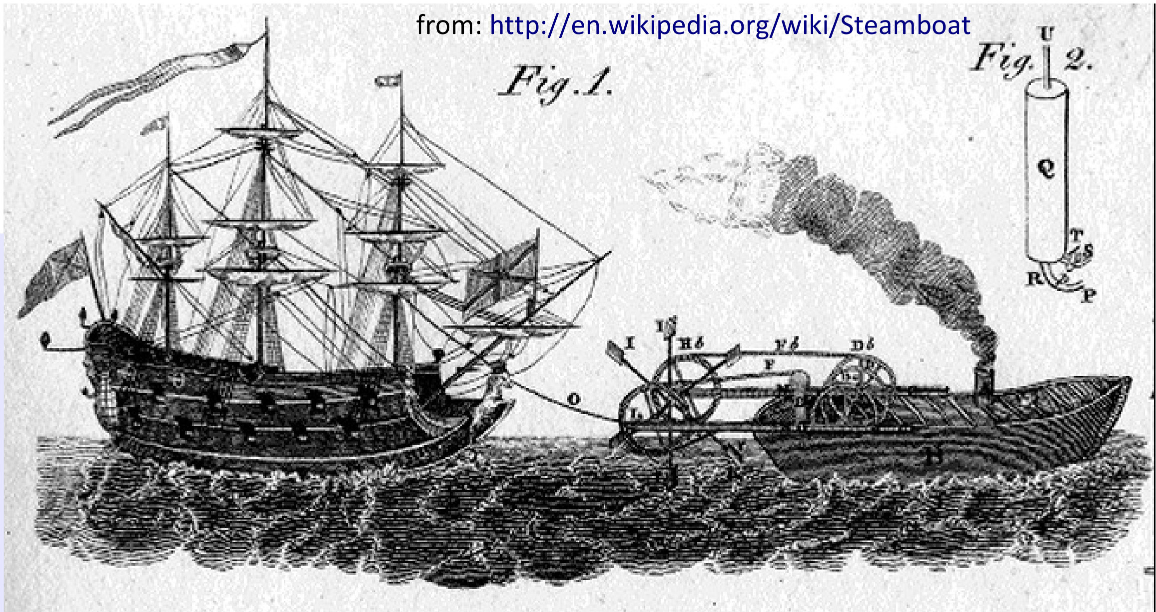
Distribution grid: electricity in = electricity out
Chaotic wind locks in future natgas demand
http://comste.gov.ph/content.asp?code=292
http://www.vtt.fi/inf/pdf/publications/2004/P554.pdf
Similarity **CAES**: natural gas fired "storage"

CAES – Compressed Air Energy "Storage":
"McIntosh CAES plant requires 0.69kWh of electricity and 1.17kWh of gas for each 1.0kWh of electrical output. A non-CAES natural gas plant can be up to 60% efficient therefore uses 1.67kWh of gas per kWh generated. "
http://en.wikipedia.org/wiki/Compressed_air_energy_storage



Real energy storage R&D needed (also EVs)

Subsidies to deploy contemporary tech. do not address these issues but lock in contemporary problems



from: http://en.wikipedia.org/wiki/Steamboat

“Renewable” energy policy in Europe

Driven by rising demand, record high oil and natural gas prices, concerns over energy security and an aversion to nuclear energy, European countries are expected to put into operation about **50 coal-fired plants over the next five years, plants that will be in use for the next five decades.** [NY Times 4/23/2008]

http://www.nytimes.com/2008/04/23/world/europe/23coal.html

Mandated buyouts of “renewable” electricity independently of demand for multiple times the market price
Contra-efficient: Scarce resources → shift of capital from R&D to production of inefficient renewable resource extractors

Cap and trade – Europe spent 50 billion EUR and emission increased
Now **50 new coal power plants** under construction or planned

Germany – renewables are demonstratively not the answer
- 26 new coal plants under construction or planned
- New natural gas pipeline build by Gazprom (51%) and others
- Gerhard Schroeder – chairman of the shareholders committee

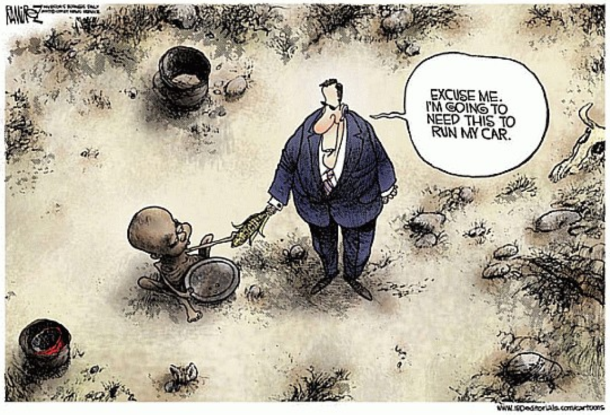
Austria – replaced Zwentendorf NPP by Dürnrohr coal burner
- 4 600 MW in natgas burners in construction or planned
- imports 10% and rising

France, **Sweden**, etc demonstrated than nuclear works, and does displace carbon fuels combustion, see slide 13 & 21

Dependency on natural gas imports for electricity and heating is also a national security issue

References: http://pathsoflight.us/musing/?p=202
http://www.spiegel.de/international/germany/0,1518,472786,00.html
http://www.businessweek.com/globalbiz/content/mar2007/gb20070321_923592.htm
http://www.businessweek.com/globalbiz/content/feb2009/gb20090210_228781.htm
http://en.wikipedia.org/wiki/Nord_Stream
http://www.washingtonpost.com/wp-dyn/content/article/2005/12/12/AR2005121201060.html
http://ekonomika.ihned.cz/?m=d&article[id]=20266960

Industrial boifuels = major disaster



Modern industrial agriculture = oil (mech., fertilizers, processing) → food
Burning food?!?

"More fossil energy is used to produce ethanol from corn than the ethanol's calorific value." T. W. Patzek, UC Berkeley
http://petroleum.berkeley.edu/papers/patzek/CRPS416-Patzek-Web.pdf
"Sugarcane-for-ethanol plantation in Brazil could be "sustainable" if the cane ethanol powered a 60%-efficient fuel cell that does not exist."
http://petroleum.berkeley.edu/papers/patzek/CRPS-BiomassPaper.pdf

Environmental wreckage from intensive agriculture http://www.biofuelwatch.org.uk/

Competition for scarce resources (land, labor, energy) with food crops increases food prices
→ 100 M people pushed to poverty http://www.nytimes.com/2008/10/08/world/europe/08italy.html?ref=world

Actually spend more fossil inputs for the same distance traveled, "Biofuels make climate change worse"
http://www.independent.co.uk/environment/climate-change/biofuels-make-climate-change-worse-scientific-study-concludes-779811.html

OECD report: "The rush to energy crops threatens to cause food shortages and damage to biodiversity with limited benefits"
http://media.ft.com/cms/fb8b5078-5fdb-11dc-b0fe-0000779fd2ac.pdf

UN experts calling to stop subsidizing boifules immediately
http://www.livescience.com/environment/071027-ap-biofuel-crime.html

Perhaps oceanic algae? – closed cycle
http://www.nrel.gov/docs/legosti/fy98/24190.pdf http://www.oilgae.com/
http://www.popularmechanics.com/science/earth/4213775.html

Waste boimass works, but already all used

Issues with nuclear energy

Waste, Proliferation, Safety, Peak Uranium ← not really a problem (IMHO, many differ)
Costs, Scalability, Sustainability ← issues to be addressed

Waste – (partially) spent nuclear fuel (SNF)

- **Low volume & solid** → easy to store separated from biosphere
- **Zero casualties** from all commercial SNF storage
- **Resource** for next generation nuclear power, and rare materials (Tc, Ru, Rh, Pd, Xe)

Safety – long term established track record

- US nuclear industry is safer than working in financial industry
- Actually fission is the safest energy resource ever, in terms of both relative and absolute casualties
- Engineered “defense in depth” - adds complexity and expenses

Proliferation – a non issue for civilian nuclear energy

Using materials from civilian cycle is harder than to start from scratch, besides security issues
heavy shielding, remote machining, rad damage to electronics, RG-Pu – 11.2 W/kg heat, “150W bulb wrapped by explosives...”
http://enochthered.wordpress.com/2009/03/02/nuclear-power-and-terrorist-proliferation-of-nuclear-weapons/

Home made nukes impossible – requires easily detectable industry

States which desire nuclear armament follow long time established, well documented routes directly to weapon grade materials, several designs available including warheads

Apparently replication of these 60 years old processes is rather simple, as demonstrated in 2006 by isolated & starving North Korea http://en.wikipedia.org/wiki/2006_North_Korean_nuclear_test

=> **nuclear weapon proliferation is an issue for international politics**

Nuclear energy can help with quality of life, thus decreasing societal tension in regions.

Appropriate regulations of nuclear materials and safety necessary for the above
However, nuclear regulators task: minimizing risks from nuclear energy; without considering the risks of not using nuclear energy => stagnation

Conclusions

Affordable energy is mandatory for progress of humanity

Scarcity of **materials** – **recycle** with **plasma arc** technology

Energy generation problematic, due to **huge externalities** and **un-sustainability of fossil fuels**

Solar renewables, energy storage – invest into R&D instead of subsidizing
production & deployment of current expensive and combustion-dependent technology

Contemporary nuclear energy → demonstratively **the best energy** resource we have now

However: **problems** with **scalability** (material requirements due to highly pressurized water → cost, long term viability of uranium sources, inefficient mineral resource use → waste)

We need a better way of utilizing nuclear energy!
Which is why we went here.

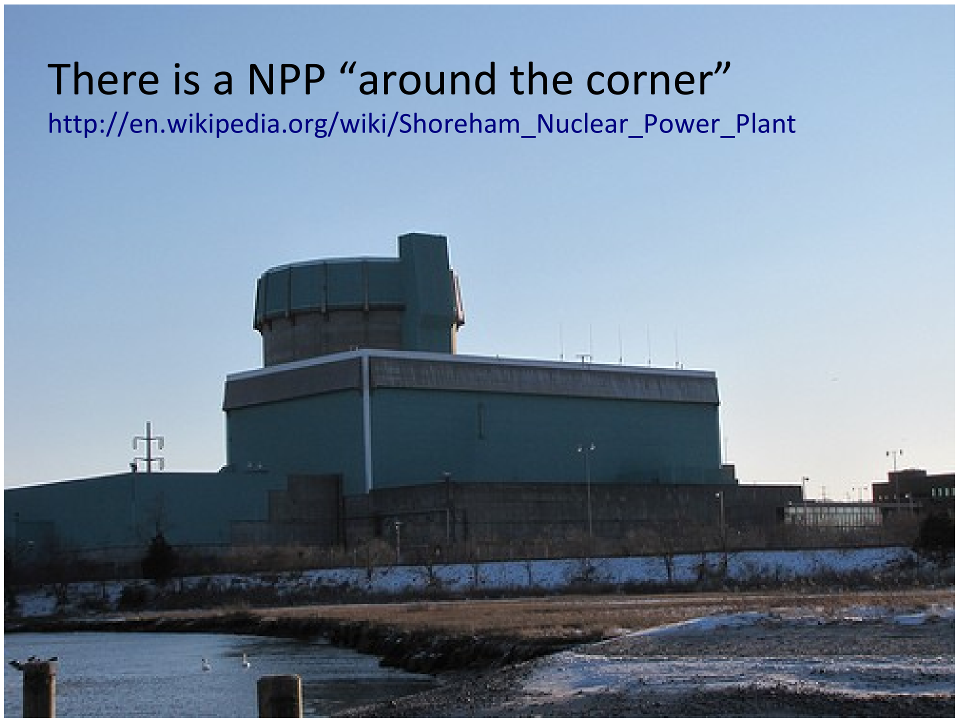
"Public opinion [is the] lord of the universe.",
"When public opinion changes, it is with the rapidity of thought."
[Thomas Jefferson on Politics & Government]
http://etext.virginia.edu/jefferson/quotations/jeff0300.htm

Backup slides

What about Long Island? Ask EPA!

Where does your electricity come from?
http://www.epa.gov/cleanenergy/energy-and-you/how-clean.html

Electricity source	[%] 11973
Oil	**59.1**
Natgas	**34.7**
Non-hydro renew. (waste inc.)	3.3
Nuclear	0
Coal	0
Hydro	0



If some says "nuclear does not help with oil problem", beware.

Similar case in Austria:
Start Zwentendorf!
http://plarmy.org/zwentendorf/en/

Start Shoreham? E-mail me if interested!

Ondřej Chvála, chvala@bnl.gov

Power Generation Resource Inputs

concrete+steel are > 95% construction costs

- **Nuclear**: 1970's vintage PWR, 90% capacity factor, 60 year life [1]
  - 40 t steel / MW(average)
  - 190 m3 concrete / MW(average)

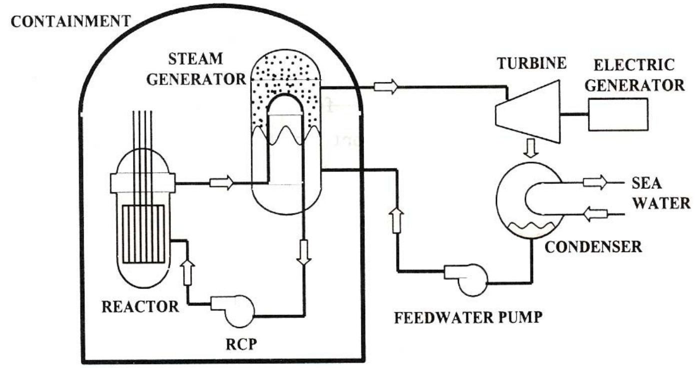
- **Wind**: 1990's vintage, 6.4 m/s average wind speed, 25% capacity factor, 15 year life [2]
  - 460 t steel / MW (average)
  - 870 m3 concrete / MW(average)

- **Coal**: 78% capacity factor, 30 year life [2]
  - 98 t steel / MW(average)
  - 160 m3 concrete / MW(average)

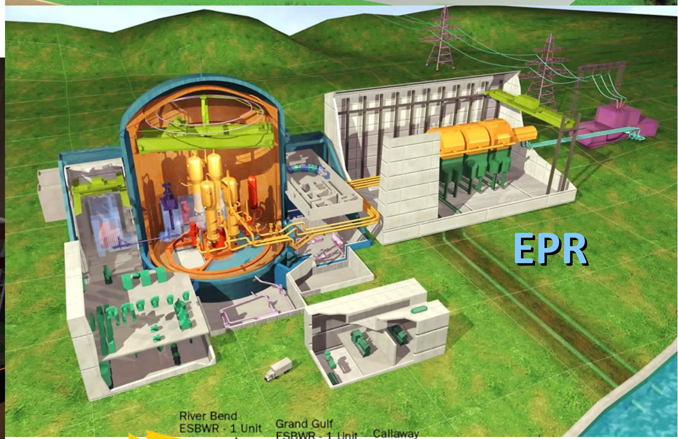
- **Natural Gas Combined Cycle**: 75% capacity factor, 30 year life [3]
  - 3.3 t steel / MW(average)
  - 27 m3 concrete / MW(average)

1. R.H. Bryan and I.T. Dudley, "Estimated Quantities of Materials Contained in a 1000-MW(e) PWR Power Plant," Oak Ridge National Laboratory, TM-4515, June (1974)
2. S. Pacca and A. Horvath, Environ. Sci. Technol., 36, 3194-3200 (2002).
3. P.J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," U. WisconsinReport UWFDM-1181, August, 2002

Contemporary nuclear energy

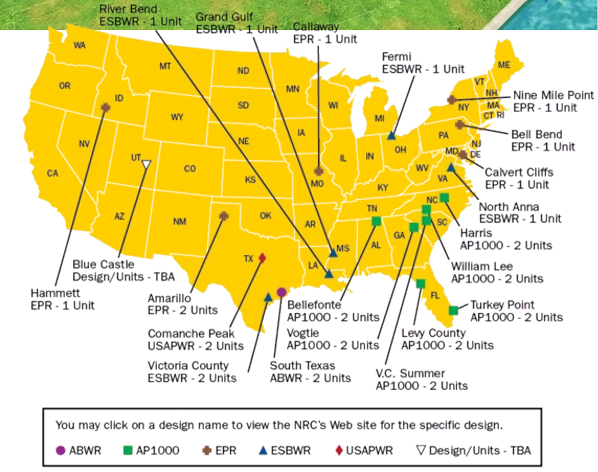


Originates in 1950's navy reactors:
1953 reactor, 1955 Nautilus
Nautilus museum http://www.ussnautilus.org
http://en.wikipedia.org/wiki/S1W_reactor



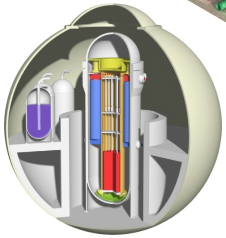
By large PWRs: UO2 fuel, 5% enrichment, pressurized vessel, water coolant, steam generators, steam plant

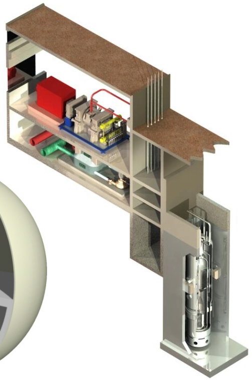
<u>World</u>: **436** operating, **44** in construction, **110** ordered/planned, **272** proposed
http://www.world-nuclear.com/info/reactors.html

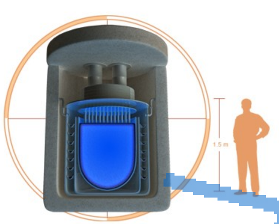


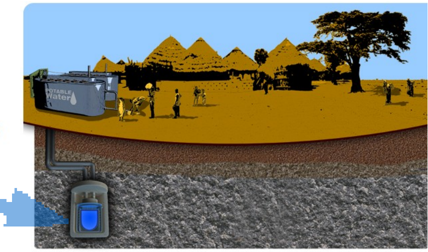
<u>USA</u>: **104** operating, **32** new orders in US-NRC pipeline
http://www.nrc.gov/reactors/new-reactors.html

Small modular reactors
Toshiba 4S, Westinghouse IRIS, nuScale PWR, Hyperion, NEREUS
http://www.world-nuclear.org/info/inf33.html
http://hulk.cesnef.polimi.it/
http://www.nuscalepower.com/
http://www.hyperionpowergeneration.com/
http://www.atomicinsights.com/AI_03-20-05.html
http://www.romawa.nl/nereus/overview.html









Current nuclear industry
could perhaps double in ~30 years, keeping **6-10% TPES** – **not enough!**

How much uranium is there?

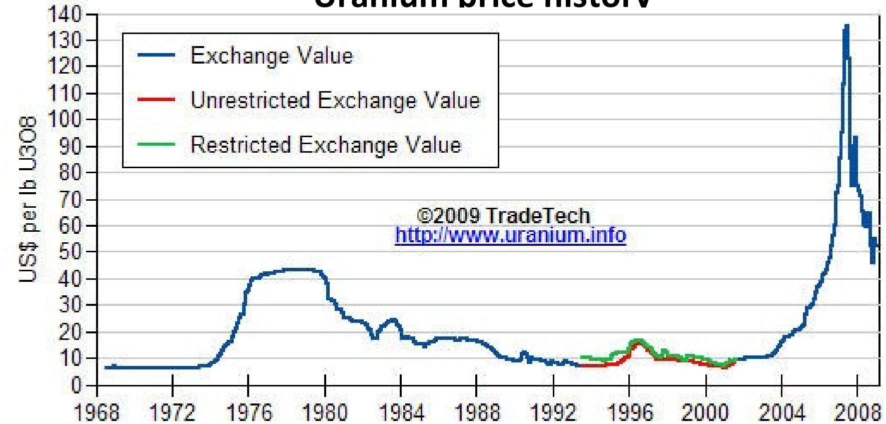
Log-normal uranium distribution

type of deposit	estimated tonnes	estimated ppm
Vein deposits	2×10^5	10,000+
Pegmatites, unconformity deposits	2×10^6	2,000-10,000
fossil placers, sand stones	8×10^7	1,000-2,000
lower grade fossil placers,sandstones	1×10^8	200-1,000
volcanic deposits	2×10^9	100-200
black shales	2×10^{10}	20-100
shales, phosphates	8×10^{11}	10-20
granites	2×10^{12}	3-10
average crust	3×10^{13}	1-3
evaporites, siliceous ooze, chert	6×10^{12}	.2-1
oceanic igneous crust	8×10^{11}	.1-.2
ocean water	2×10^{10}	.0002-.001
fresh water	2×10^6	.0001-.001

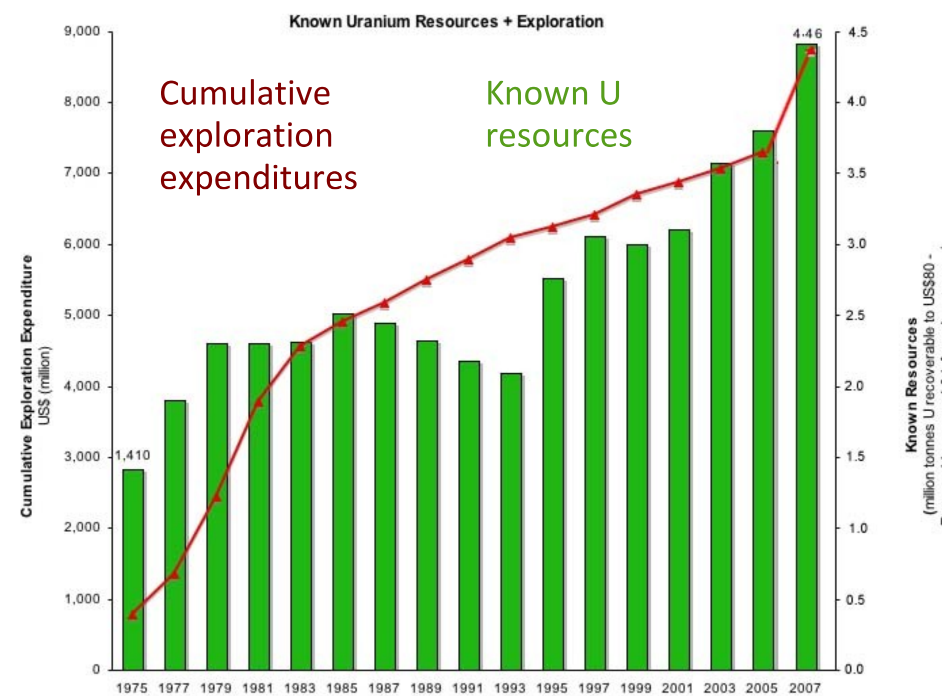
Currently known and estimated uranium resources cheaper than \$130/lb enough for ~80 years at current consumption.

References:
http://www.world-nuclear.org/info/inf75.html
http://nuclearinfo.net/Nuclearpower/UraniuamDistribution
IAEA, Uranium 2007: http://books.google.com/books?id=ABKo3wSTvt0C
http://www-pub.iaea.org/MTCD/publications/PDF/te_1033_prn.pdf
http://www.energywatchgroup.org/fileadmin/global/pdf/EWG_Report_Uranium_3-12-2006ms.pdf
http://nuclearinfo.net/Nuclearpower/WebHomeEnergyLifecycleOfNuclear_Power
http://www.world-nuclear.org/info/inf11.html

Uranium price history

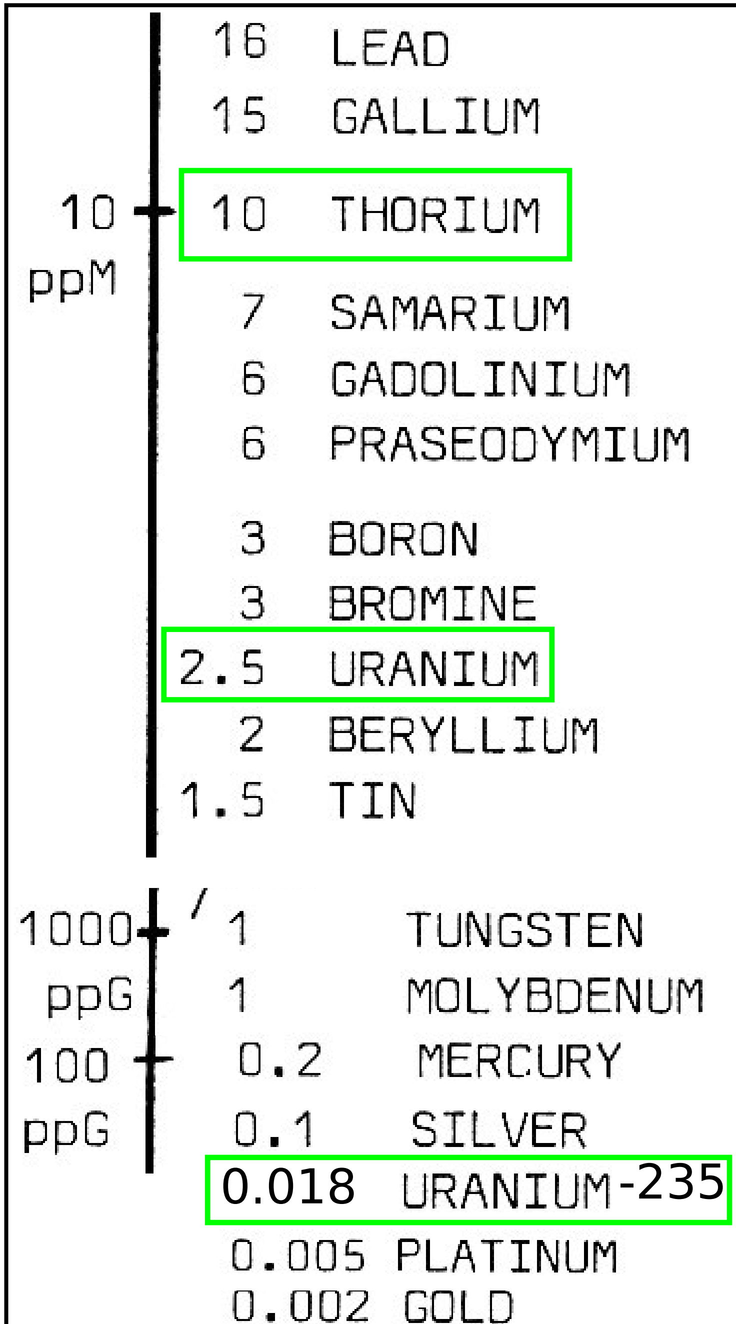


Recently used mineral, not fully prospected



year

Thorium and Uranium Abundant in the Earth's Crust



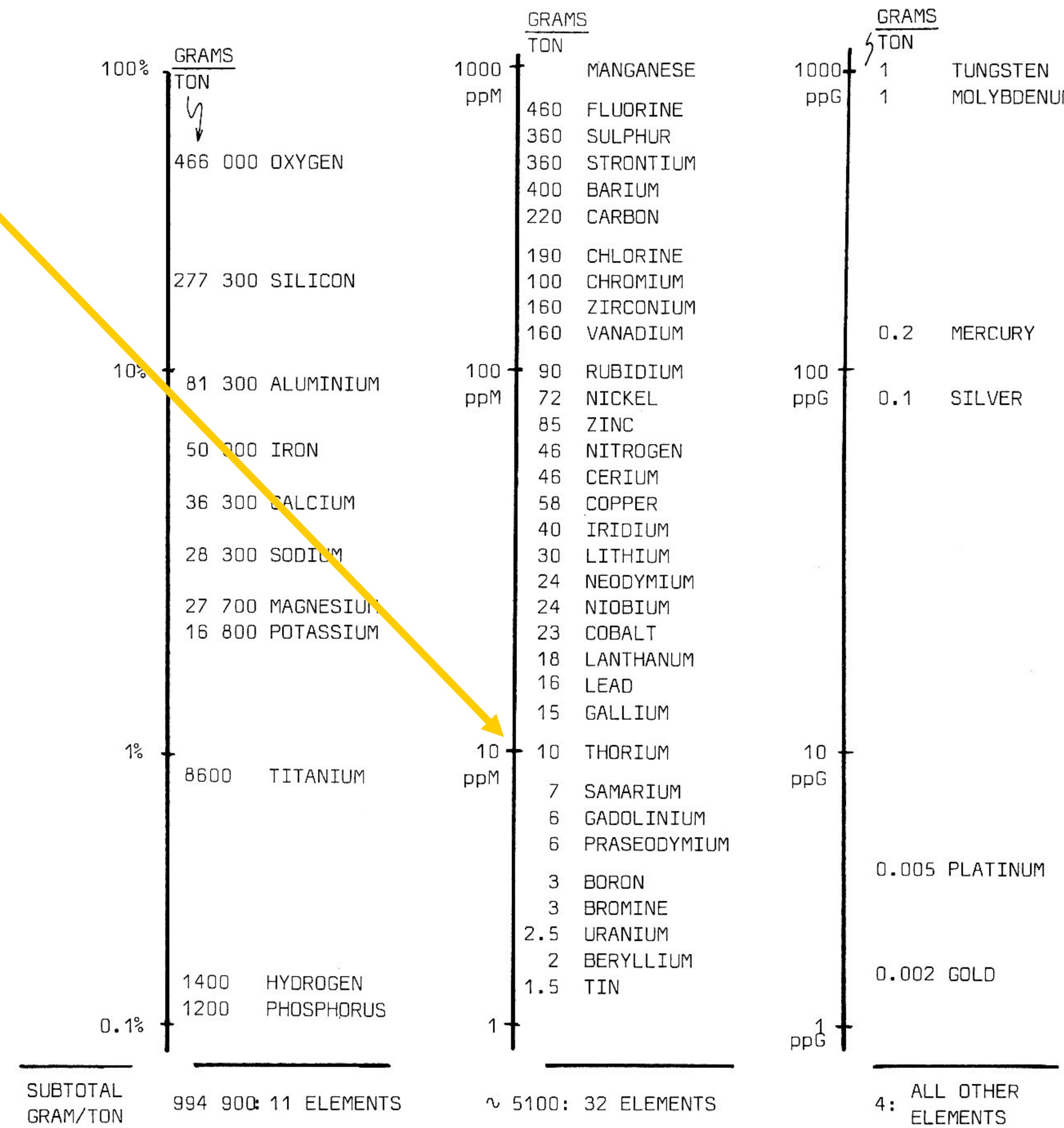
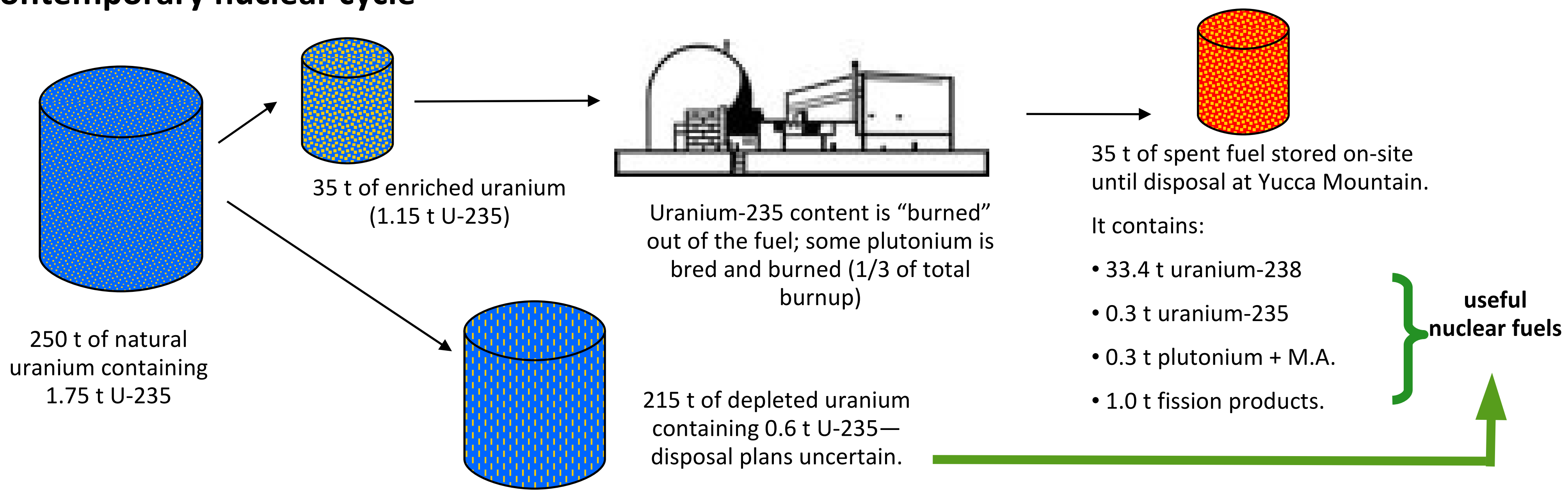


Fig. 5.13. The chemical composition of the Earth's crust.

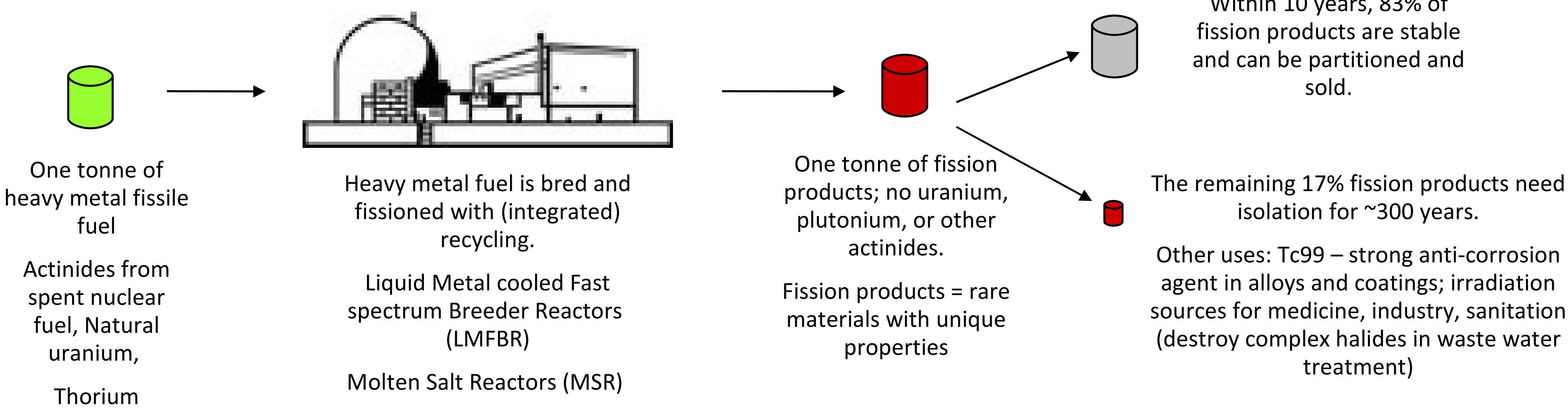
Nuclear fuel cycles

mission: make 1000 MW of electricity for one year

Contemporary nuclear cycle



Closed nuclear cycle – ~250x more efficient



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Fast breeder reactors (LMFBR)

Originally much less uranium resources known → (net) breeding essential

http://en.wikipedia.org/wiki/EBR-I

1951 – EBR1 near Arco, Idaho, first electricity from fission (Dec 22)
1953 – net breeding experimentally confirmed

~20 FBRs built, ~300 reactors years of experience, 3 operating

US. research (Integral Fast Reactor, IFR) killed in 1994,
some revival by GNEP (GE-Hitachi PRISM, metallic fuel,
integrated proliferation resistant pyro-processing)
French research (Superfenix → EFR) killed by politics in 1996

Development in Russia, India, Japan, South Korea, Italy

Advantages: Unlimited fuel supply, Operation close to atmospheric pressure, Passive safety demonstrated during IFR development, little R&D needed

Disadvantages: High fissile load (12 t for Na, 20 t for Pb coolant for 1GWe) – can only start <100 reactors,
Not that high temperature for direct heat utilization (550 C = 1022 F), Public Perception,
Net breeding (used to be advantage) may be problematic, Cost?

Fast reactor summary references:
http://www.world-nuclear.org/info/inf98.html
http://www.world-nuclear.org/info/inf08.html

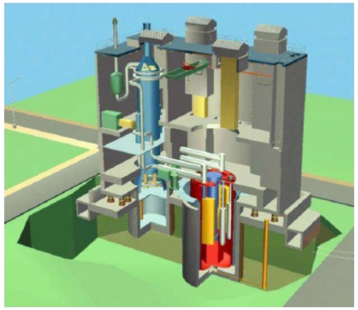
Integral Fast Reactor links:
http://www.prescriptionfortheplanet.com/ ← **recommended book**
http://bravenewclimate.com/2009/02/12/integral-fast-reactors-for-the-masses/
http://skirsch.com/politics/globalwarming/ifr.htm

Uranium resource with closed cycle:
http://www-formal.stanford.edu/jmc/progress/cohen.html
http://sustainablenuclear.org/PADs/pad11983cohen.pdf

SuperPhenix
http://en.wikipedia.org/wiki/Superph%C3%A9nix
http://lpsc.in2p3.fr/gpr/sfp/superphenix.html

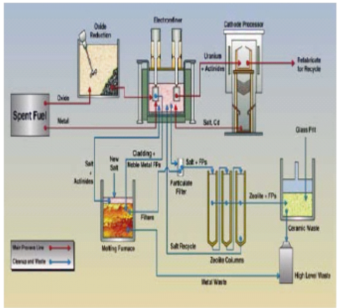
GE-Hitachi PRISM

PRISM



- 840 MWth & 311 MWe
- Na cooled fast reactor
- Passive safety
- Modular/scalable
- Factory built
- Flexible fuel cycle (broad input composition)
- Metal or oxide fuel (metal pref.)
- Extensive component testing

Electro Refining



- Modular/scalable
- Sized to support ABR
- Proliferation resistant
- Removal of volatile FP through voloxidation
- Continuous or batch process
- Extensive testing in the U.S., Russia, Japan, and Korea
- Used by industrial refiners

imagination at work

3
GE
2/15/2007

NRC's NUREG-1368 Concluded

- No obvious impediments to licensing the PRISM (ALMR) design have been identified
- There are eight design features that deviated from LWRs
  - accident evaluation
  - calculation of source term
  - containment
  - emergency planning
  - staffing
  - heat removal
  - positive void
  - control room design

imagination at work

IFR++ revised under GNEP
Metallic fuel: Zr-U-Pu alloy
Integrated fuel cycle: fuel pins melted, electro-refined (FPs separated from useful nuclear fuels), re-casted, re-used
Proliferation resistant – no Pu separation

GE: "Advanced Recycling Centers" (ARC) burn SNF, WG-Pu, DU

26 ARCs consume 120K t SNF
Avoid 400 Mt CO2/year
Produce 50 GWe @ $46/MWhr

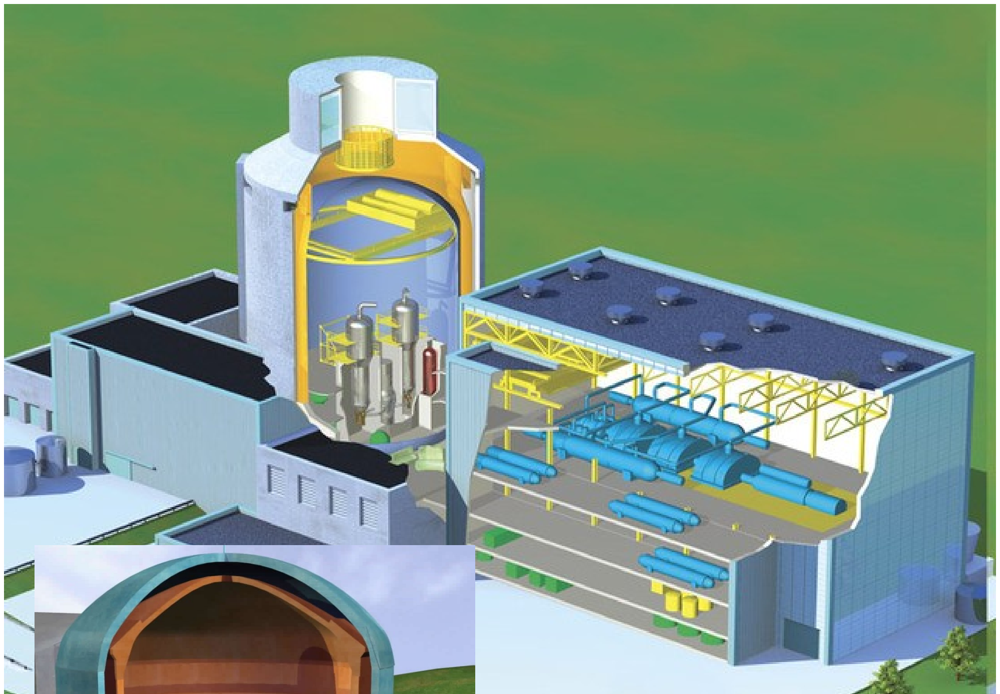
Timeline: within 5-15 years fuel qualification program with a test reactor

GE-Hitachi slides:
http://local.ans.org/virginia/meetings/2007/2007RIC.GE.NRC.PRISM.pdf
http://www.energyfromthorium.com/gnep/GE-Hitachi%20Presentation.p

NUREG-1368:
http://www.osti.gov/bridge/product.biblio.jsp?osti_id=10133164

PWR vs. LMFBR comparison

Pressurized Water Reactor (PWR)
Westinghouse AP1000



Areva EPR (PWR)

LMFBR
GE-Hitachi PRISM
(turbine and generator not shown)

No steam expander and condenser
No huge containment needed
Reactor and fuel electro-refining
small enough for underground location

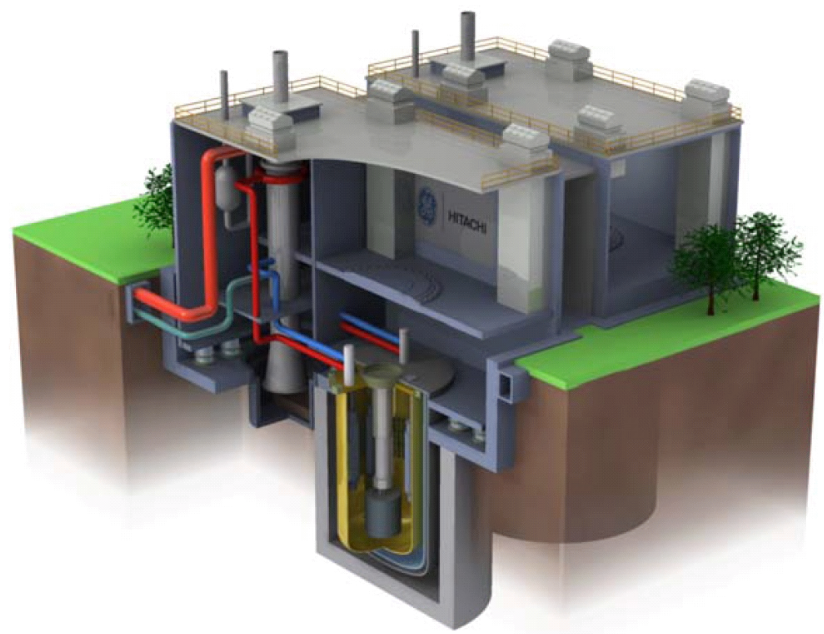
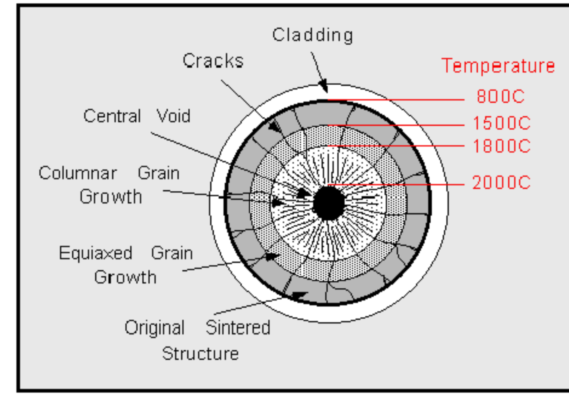


Figure 2: PRISM Reactor power block used to produce electricity from spent nuclear fuel.

Can we do better? Goal: Cheaper than coal!

Solid fuels – deformations (swelling) & accumulation of fission products (degradation of solid fuel matrix, neutron poisons) **limit achievable burn-up**
Expensive fuel manufacturing, burnable poisons, excess reactivity to compensate short term FPs, shutdowns for fuel rotation necessary. Waste, reprocessing.



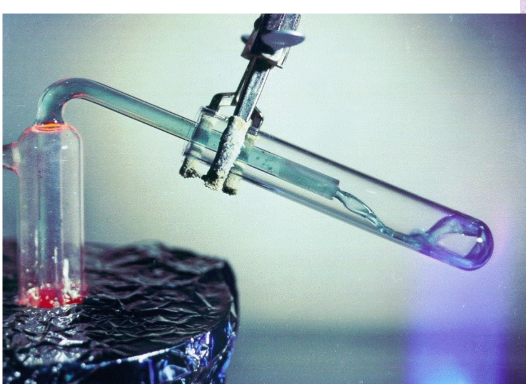
Fluid fuels, in particular **molten fluoride salts** – ionic bonds; Thorium

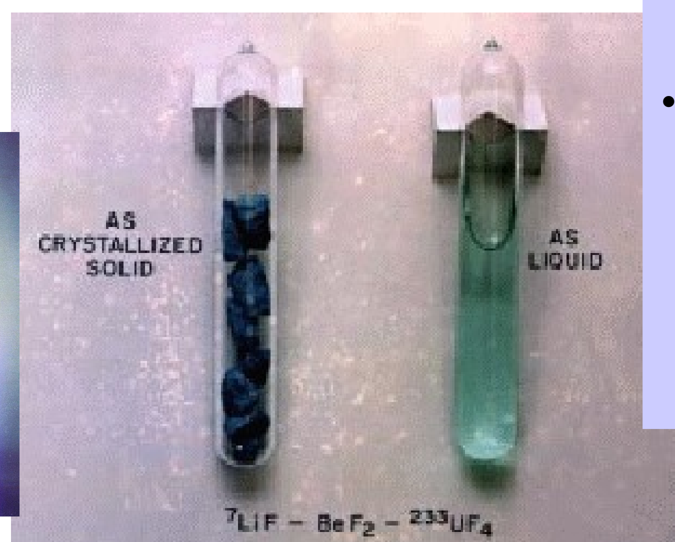
The birth of the Liquid Fluoride Reactor

The liquid-fluoride nuclear reactor was invented by Ed Bettis and Ray Briant of ORNL in 1950 to meet the unique needs of the Aircraft Nuclear Program.

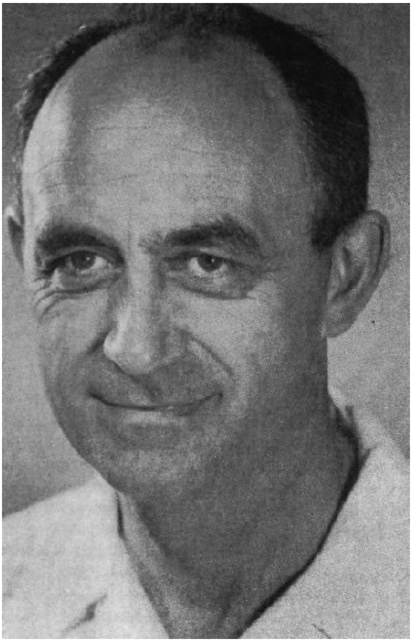
Fluorides of the alkali metals were used as the solvent into which fluorides of uranium and thorium were dissolved. In liquid form, the salt had some extraordinary properties!

- Very high negative reactivity coefficient
  - Hot salt expands and becomes less critical
  - Reactor power would follow the load (the aircraft engine) without the use of control rods!
- Salts were stable at high temperature
  - Electronegative fluorine and electropositive alkali metals formed salts that were exceptionally stable
  - Low vapor pressure at high temperature
  - Salts were resistant to radiolytic decomposition
  - Did not corrode or oxidize reactor structures
- Salts were easy to pump, cool, and process
  - Chemical reprocessing was much easier in fluid form
  - Poison buildup reduced, breeding enhanced
  - "A pot, a pipe, and a pump…"
  - Whole new landscape of possible reactor geometries

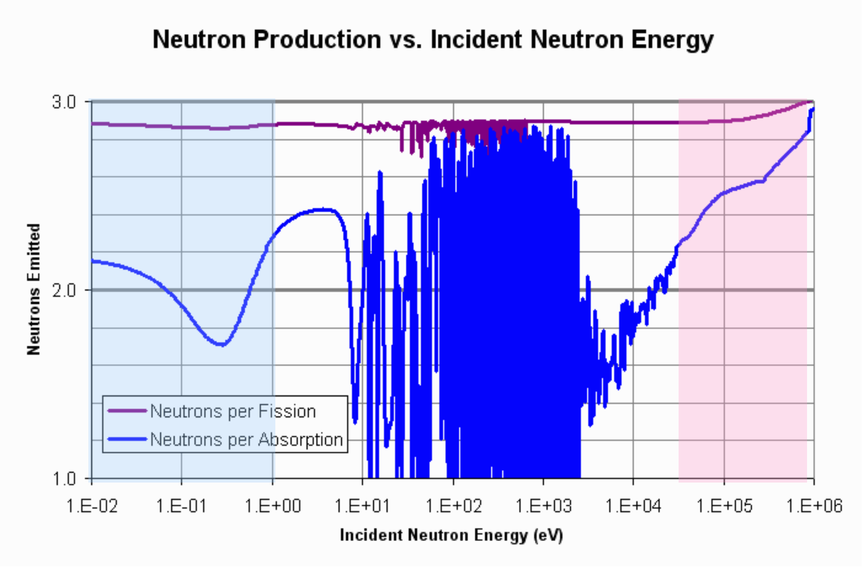




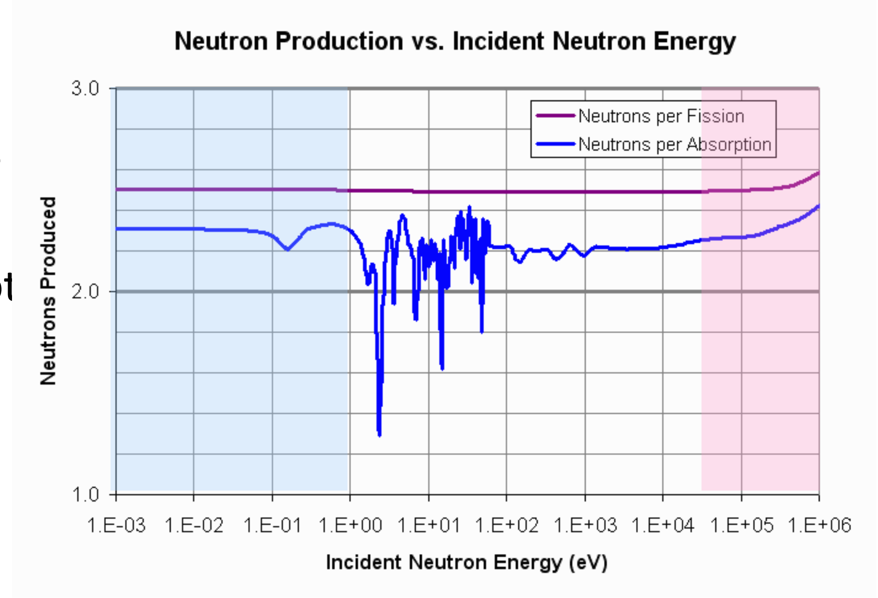
1944: A tale of two isotopes…



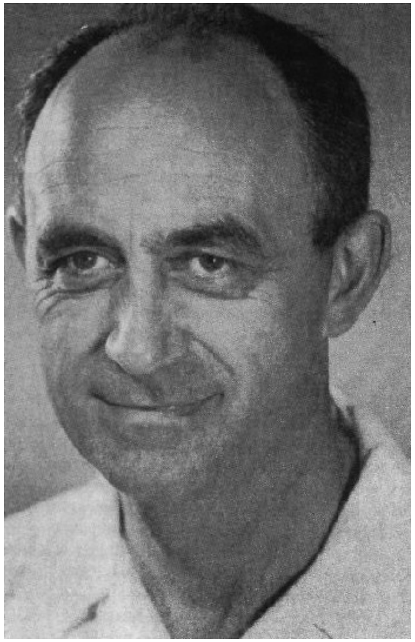
- Enrico Fermi argued for a program of fast-breeder reactors using uranium-238 as the fertile material and plutonium-239 as the fissile material.
- His argument was based on the breeding ratio of Pu-239 at fast neutron energies.
- Argonne National Lab followed Fermi's path and built the EBR-I and EBR-II (IFR).



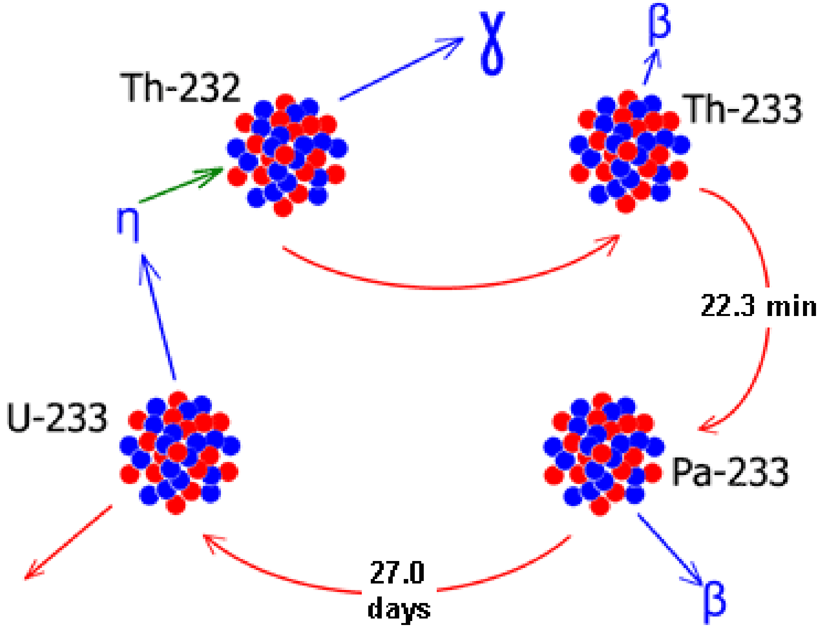
- Eugene Wigner argued for a thermal-breeder program using thorium as the fertile material and U-233 as the fissile material.
- Although large breeding gains were not possible, thermal spectrum breeding was possible, with advantages
- Wigner's protégé, Alvin Weinberg, followed Wigner's path at the Oak Ridge National Lab.



1944: A tale of two isotopes…



"But Eugene, how will you reprocess the thorium fuel effectively?"

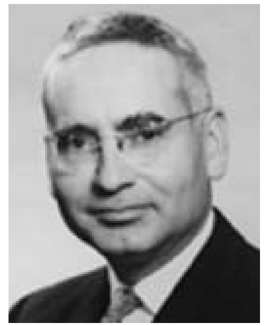


Thorium Fuel Cycle

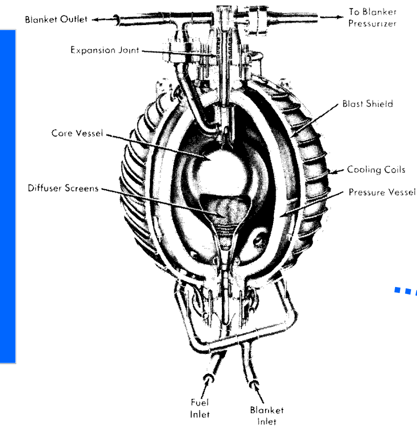
"We'll build a fluid-fueled reactor, that's how…"

ORNL Fluid-Fueled Thorium Reactor Progress (1947-1960)

1947 – Eugene Wigner proposes a fluid-fueled thorium reactor



1950 – Alvin Weinberg becomes ORNL director



1952 – Homogeneous Reactor Experiment (HRE-1) built and operated successfully (100 kWe, 550K)

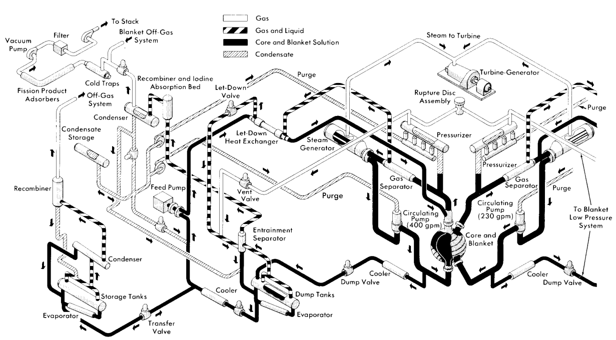
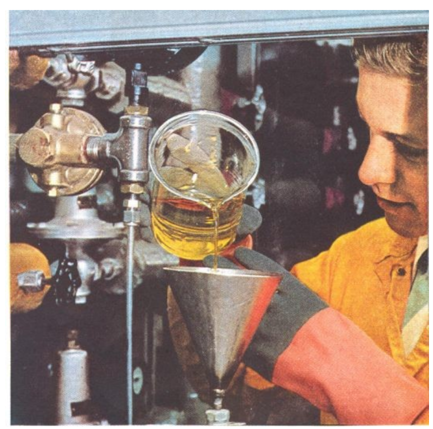


Fig. 7-7. Flowsheet of HRE-2.

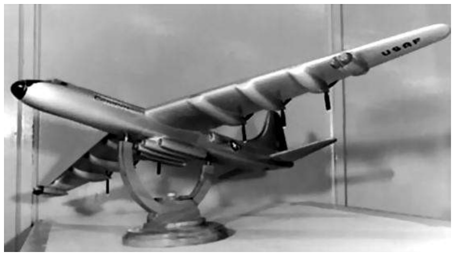


1959 – AEC convenes "Fluid Fuels Task Force" to choose between aqueous homogeneous reactor, liquid fluoride, and liquid-metal-fueled reactor. Fluoride reactor is chosen and AHR is canceled

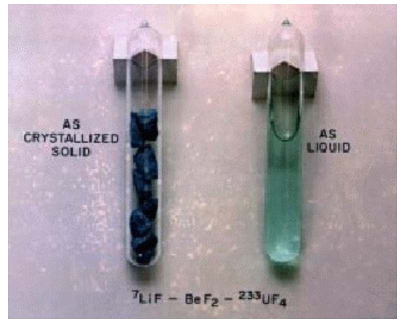
Weinberg attempts to keep both aqueous and fluoride reactor efforts going in parallel but ultimately decides to pursue fluoride reactor.

1958 – Homogeneous Reactor Experiment-2 proposed with 5 MW of power

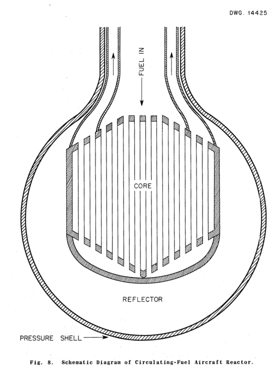
ORNL Aircraft Nuclear Reactor Progress (1949-1960)

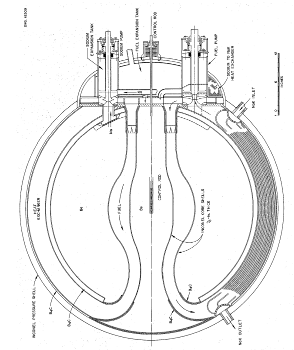


1949 – Nuclear Aircraft Concept formulated

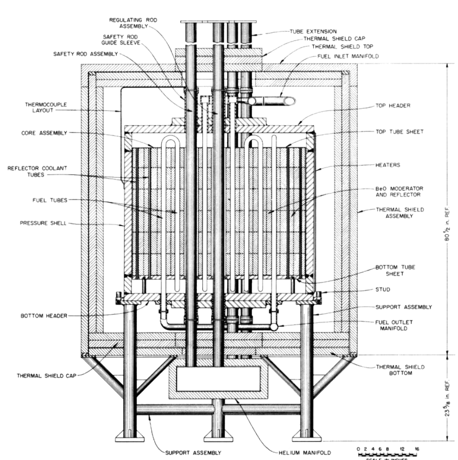


1951 – R.C. Briant proposed Liquid-Fluoride Reactor

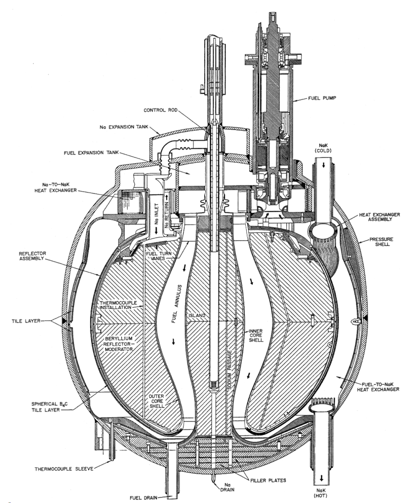




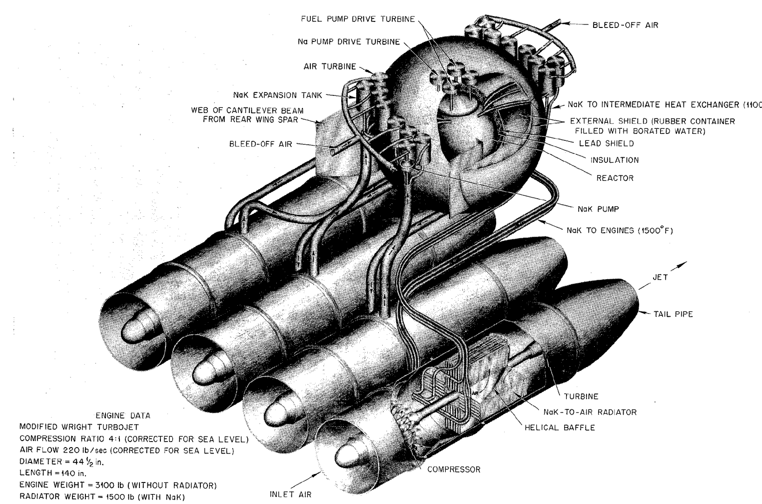
1952, 1953 – Early designs for aircraft fluoride reactor



1954 – Aircraft Reactor Experiment (ARE) built and operated successfully (2500 kWt2, 1150K)



1955 – 60 MWt Aircraft Reactor Test (ART, “Fireball”) proposed for aircraft reactor



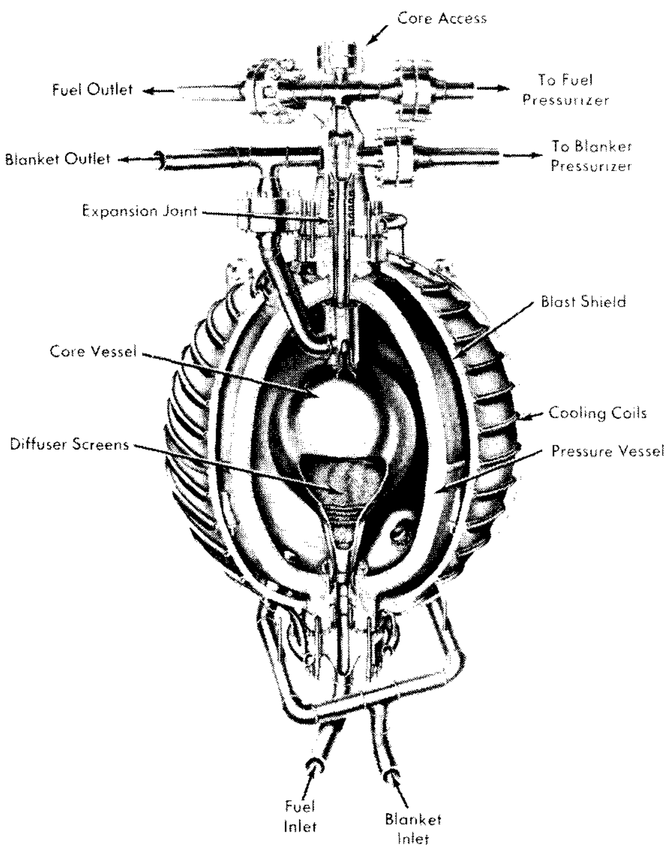
1960 – Nuclear Aircraft Program canceled in favor of ICBMs

http://en.wikipedia.org/wiki/Aircraft_Reactor_Expe

Fluid-Fueled Reactors for Thorium Energy

Aqueous Homogenous Reactor (ORNL)

- Uranyl sulfate dissolved in pressurized heavy water.
- Thorium oxide in a slurry.
- Two built and operated.



Liquid-Fluoride Reactor (ORNL)

- Uranium tetrafluoride dissolved in lithium fluoride/beryllium fluoride.
- Thorium dissolved as a tetrafluoride.
- Two built and operated.

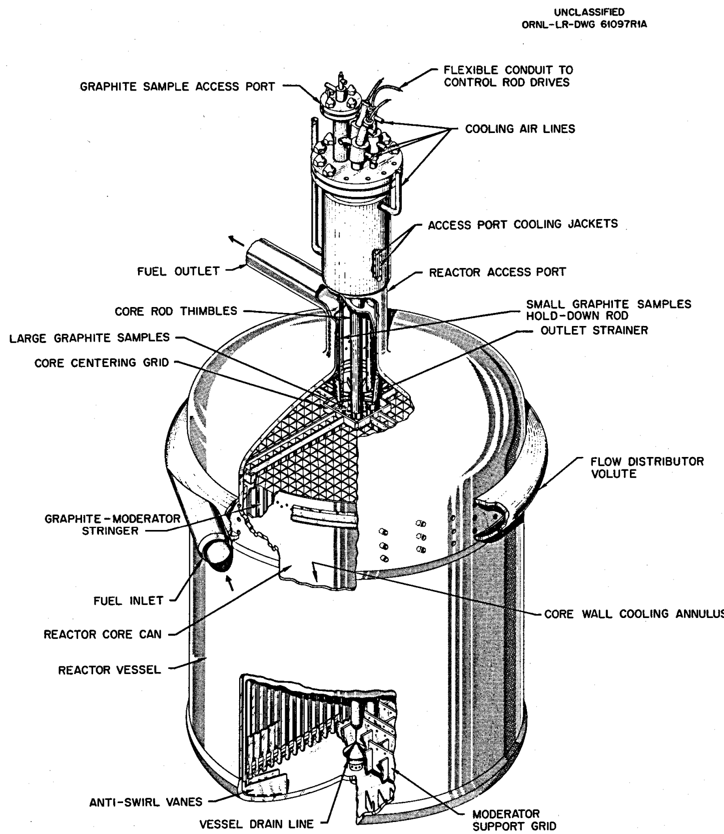
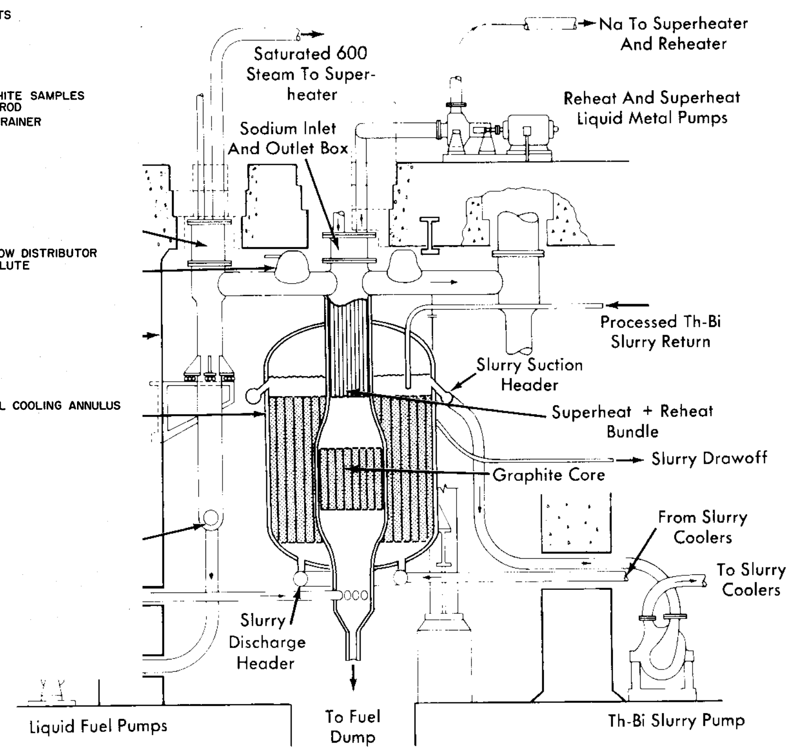


Fig. 6. MSRE Reactor Vessel.

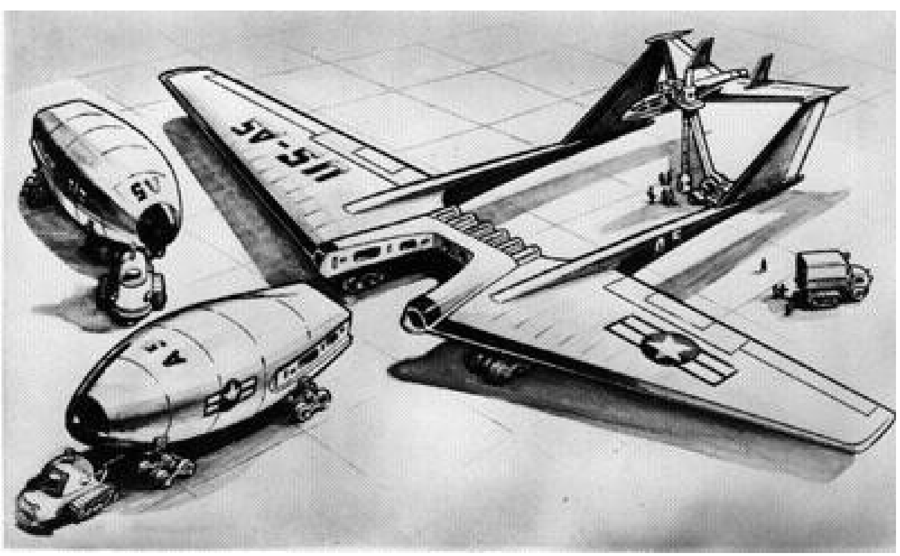
Liquid-Metal Fuel Reactor (BNL)

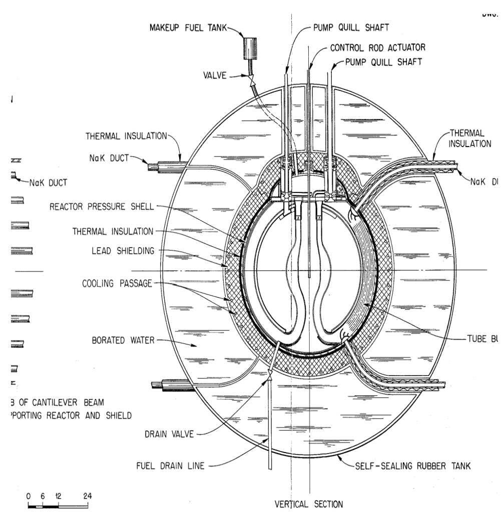
- Uranium metal dissolved in bismuth metal.
- Thorium oxide in a slurry.
- Conceptual—none built and operated.



Ondřej Chvála, chvala@bnl.gov

Aircraft Nuclear Program allowed ORNL to develop reactors





It wasn't that I had suddenly become converted to a belief in nuclear airplanes. **It was rather that this was the only avenue open to ORNL for continuing in reactor development.**

That the purpose was unattainable, if not foolish, was not so important:

A high-temperature reactor could be useful for other purposes even if it never propelled an airplane…

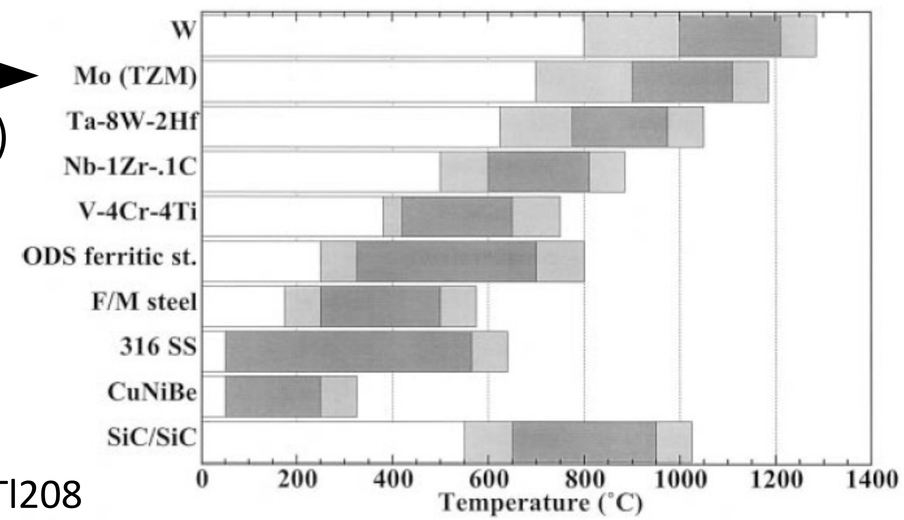
—Alvin Weinberg

Why the recent interest?

Issues with fossil fuels are getting more and more troubling
Looking for more sustainable but affordable energy resource, high heat for industry
"The second nuclear age"

Several recent advances in key technologies

- large scale Brayton cycle heat machines (jet engines, natgas turbines)
- more industrial experience with molten salts
- material research in fusion energy
- robotic manipulation and control (hot cell operation)
- some outstanding issues solved recently
  - (plumbing problem)



Operating temperature windows (based on radiation amage and thermal creep considerations)

Shift of focus – maximum breeding less important
sustainability, scalability, proliferation resistance

Proliferation resistance – U232 inevitably formed in Th cycle, Tl208 in its decay chain is a strong gamma emitter 2.6MEV

Table 2: Unshielded working hours required to accumulate a 5 rem dose (5 kg sphere of metal at 0.5 m one year after separation)

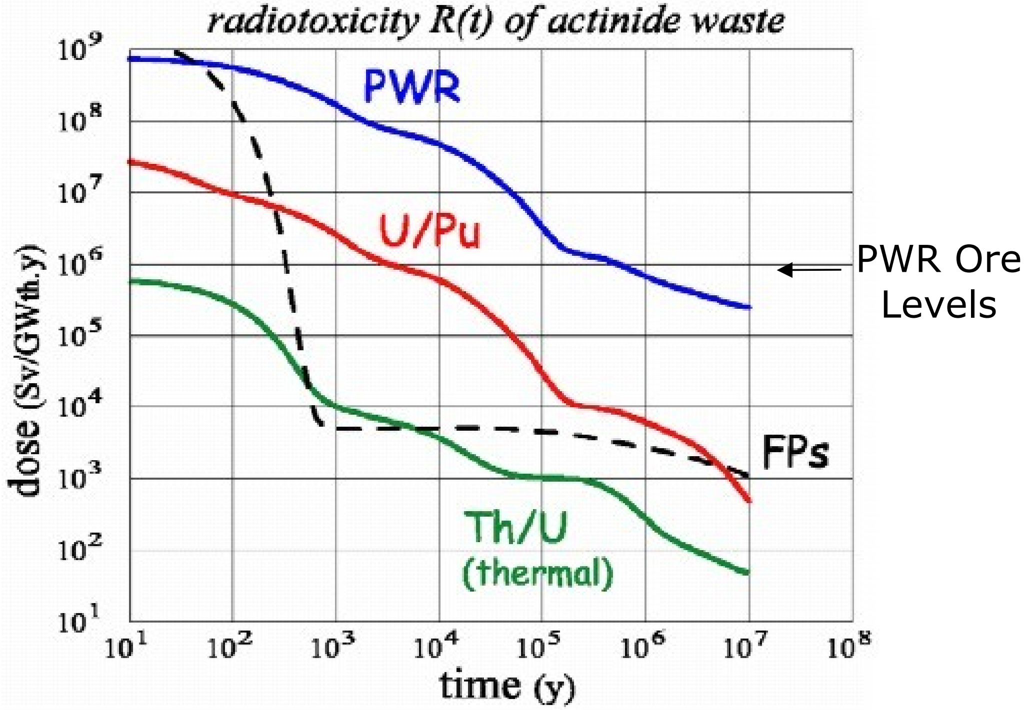
Metal	Dose Rate (rem/hr)	Hours
Weapon-grade plutonium	0.0013	3800
Reactor-grade plutonium	0.0082	610
U-233 containing 1ppm U-232	0.013	380
U-233 containing 5ppm U-232	0.059	80
U-233 containing 100 ppm U-232	1.27	4
U-233 containing 1 percent U-232	127	0.04

General Benefits of Any Molten Salt Design

Salts are chemically stable, have high boiling point, operate at low pressure
- several salt choices, melting points 400-800C, boiling points 1400-1600C
- high thermal efficiency (48%), direct use of high temperature heat

Fuel salt at the lowest pressure of the circuit, the opposite of a LWR
Volatile fission products continuously removed and stored, including Xenon.
Control rods or burnable poisons not required so very little excess reactivity
Low fissile inventory
Freeze plug melts upon fuel overheating to drain to critically safe,
- passively cooled dump tanks

Ideal for LWR TRU waste destruction
Ability to use closed thorium cycle
Only consume 800 kg thorium per GW/year
Transuranic waste production extremely low
Much lower long term radiotoxicity



Turns waste management into 500 year job, not nearly a million year
(taken from David LeBlanc's talk)

Edward Teller promoted MSR to the last month of life

THORIUM-FUELED UNDERGROUND POWER PLANT BASED ON MOLTEN SALT TECHNOLOGY

FISSION REACTORS

TECHNICAL NOTE

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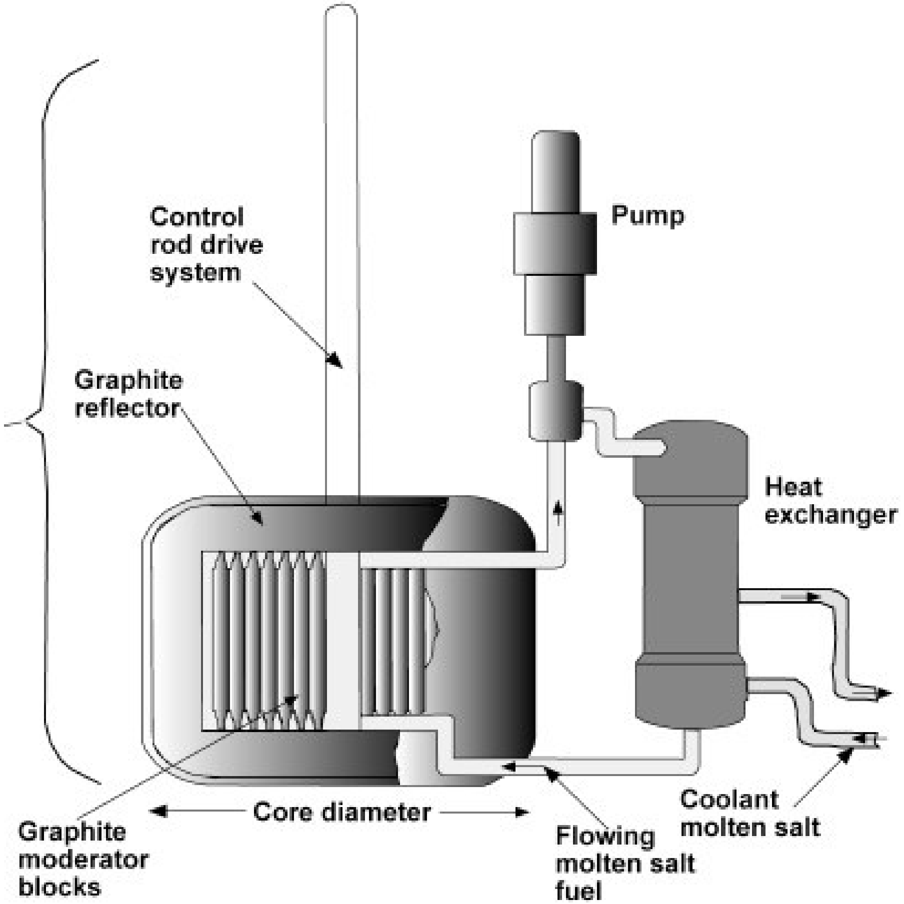

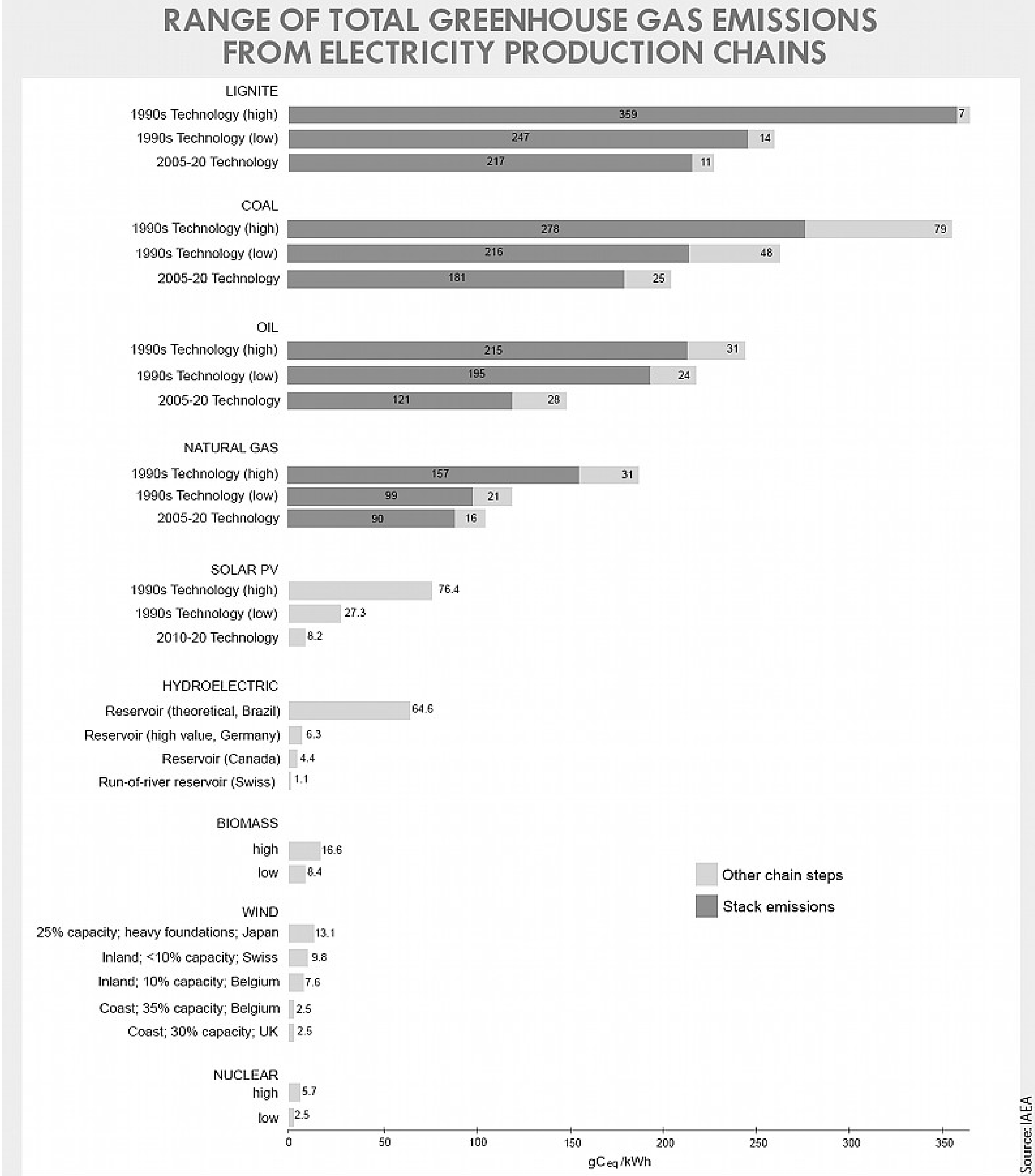
RANGE OF TOTAL GREENHOUSE GAS EMISSIONS FROM ELECTRICITY PRODUCTION CHAINS
LIGNITE
1990s Technology (high)
359
7
1990s Technology (low)
247
14
2005-20 Technology
217
11
COAL
1990s Technology (high)
278
79
1990s Technology (low)
216
48
2005-20 Technology
181
25
OIL
1990s Technology (high)
215
31
1990s Technology (low)
195
24
2005-20 Technology
121
28
NATURAL GAS
1990s Technology (high)
157
31
1990s Technology (low)
99
21
2005-20 Technology
90
16
SOLAR PV
1990s Technology (high)
76.4
1990s Technology (low)
27.3
2010-20 Technology
8.2
HYDROELECTRIC
Reservoir (theoretical, Brazil)
64.6
Reservoir (high value, Germany)
6.3
Reservoir (Canada)
4.4
Run-of-river reservoir (Swiss)
1.1
BIOMASS
high
16.6
low
8.4
WIND
25% capacity; heavy foundations; Japan
13.1
Inland; <10% capacity; Swiss
9.8
Inland; 10% capacity; Belgium
7.6
Coast; 35% capacity; Belgium
2.5
Coast; 30% capacity; UK
2.5
NUCLEAR
high
5.7
low
2.5
Other chain steps
Stack emissions
0
50
100
150
200
250
300
350
gC$_{eq}$/kWh
Source: IAEA

Middle east & nuclear

http://www.energyfromthorium.com/forum/viewtopic.php?f=39&t=1419

Below are the nuclear aspirations of countries across the Middle East.

- Algeria aims to build its first commercial nuclear power station by around 2020 and to build another every five years after that, energy minister Chakib Khelil said in February.
- He said Algeria had atomic energy agreements with Argentina, China, France and the United States and was also in talks with Russia and South Africa.
- The OPEC member has plentiful oil and gas reserves but wants to develop other energy sources to free up more hydrocarbons for export. Algeria has big uranium deposits and two nuclear research reactors but no uranium enrichment capacity. Algeria and China agreed a year ago to cooperate on developing civilian nuclear power.
- EGYPT: -- Egypt said in Oct. 2007 it would build several civilian nuclear power stations to meet its growing energy needs.
- In December 2008 Egypt chose Bechtel Power Corp as contractor to design and consult on the country's first nuclear power plant. Bechtel offered to do the work for around 1 billion Egyptian pounds ($180 million) over a 10-year period, it said.
- Bechtel will consider five locations for the first nuclear plant, starting with Dabaa on the Mediterranean coast west of Alexandria.
- IRAN: -- Iranian President Mahmoud Ahmadinejad inaugurated its first nuclear fuel production plant on Thursday. He said the plant would produce fuel for Iran's Arak heavy water reactor.
- Iran plans to start up its first atomic power plant in mid-2009, its foreign minister said in March. Tehran says the 915-megawatt Russian-built Bushehr plant will be used only for generating electricity in the world's fourth largest oil producer. But the West ccuses Iran of covertly seeking to make nuclear weapons.
- JORDAN: -- Jordan had talks with French nuclear energy producer Areva in 2008 to construct a nuclear power reactor, Jordanian officials said.
- They said Areva was a frontrunner among several international firms in talks with the kingdom to develop a nuclear reactor to meet rising demand for power.
- Jordan has signed agreements with France, China and Canada to co-operate on the development of civilian nuclear power and the transfer of technology.
- KUWAIT: -- Kuwait is considering developing nuclear power to meet demand for electricity and water desalination, the country's ruler said in February 2009.
- "A French firm is studying the issue," daily al-Watan quoted Emir Sheikh Sabah al-Ahmad al-Sabah as saying.
- Nuclear power would save fuel that could be exported but which is currently used to generate electricity and operate water desalination plants, he said.
- LIBYA: -- Moscow and Libya said in Nov. 2008 they were negotiating a deal for Russia to build nuclear research reactors for the North African state and supply fuel.
- Officials said a document on civilian nuclear cooperation was under discussion at talks between Libyan leader Muammar Gaddafi and Russian Prime Minister Vladimir Putin.
- Under the deal, Russia would help Libya design, develop and operate civilian nuclear research reactors and provide fuel for them.
- QATAR: -- Initial Qatari interest in nuclear power plants has waned with the fall in international oil and gas prices, a Qatari official said in Nov. 2008.
- If Qatar decided to go ahead with building a nuclear plant, feasibility studies showed it would be unlikely to bring a reactor into operation before 2018.
- French power giant EDF signed a memorandum with Qatar in early 2008 for cooperation on development of a peaceful civilian nuclear power programme.
- UAE: -- The Bush administration signed a nuclear deal with the United Arab Emirates in January, despite concerns in Congress that the UAE was not doing enough to curb Iran's atomic plans. Obama has advanced this policy wholeheartedly primarily because UAE absolutely insists on it.

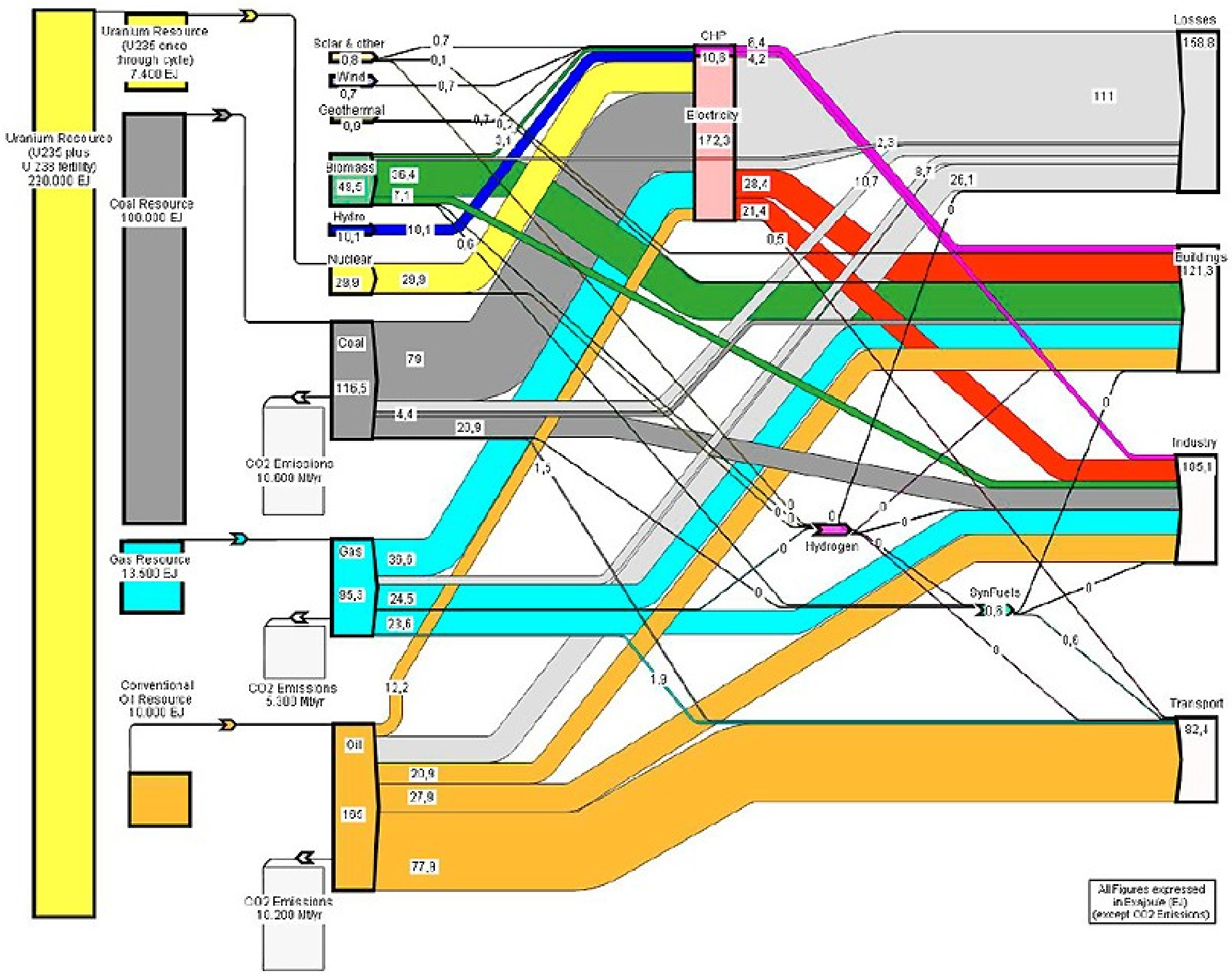

Figure 4.4: *Global energy flows (EJ in 2004) from primary energy through carriers to end-uses and losses. Related carbon dioxide emissions from coal, gas and oil combustion are also shown, as well as resources (vertical bars to the left).*

Energy Production Subsidies

Federal Financial Interventions and Subsidies in Energy Markets 2007

Table 35. Subsidies and Support to Electricity Production: Alternative Measures

Fuel/End Use	FY 2007 Net Generation (billion kilowatthours)	Alternative Measures of Subsidy and Support: Subsidy and Support Value 2007 (million dollars)	Alternative Measures of Subsidy and Support: Subsidy and Support Per unit of Production (dollars/megawatthours)
Coal	1,946	854	0.44
Refined Coal	72	2,156	29.81
Natural Gas and Petroleum Liquids	919	227	0.25
Nuclear	794	1,267	1.59
Biomass (and Biofuels)	40	36	0.89
Geothermal	15	14	0.92
Hydroelectric	258	174	0.67
Solar[1]	1	14	24.34
Wind	31	724	23.37
Landfill Gas	6	8	1.37
Municipal Solid Waste	9	1	0.13
Unallocated Renewables	NM	37	NM
Renewables (subtotal)	360	1,008	2.80
Transmission and Distribution	NM	1,235	NM
Total	4,091	6,747	1.65

NOTES: Total may not equal sum of components due to independent rounding.

Unallocated renewables include projects funded under Clean Renewable Energy Bonds and the Renewable Energy Production Incentive.

NM = Not meaningful.

[1]Net generation rounded to the nearest whole number. The actual value is 583 million kilowatthours.

Sources: Energy Information Administration, Forms EIA-906, "Power Plant Report;" Form EIA-920, "Combined Heat and Power Plant Report;" October 2006-September 2007.

Besides: wind, solar – thousands of years spent on R&D

From page 105 of the report http://www.eia.doe.gov/oiaf/servicerpt/subsidy2/index.html

Thorium, uranium, and all the other heavy elements were formed in the final moments of a supernova explosion billions of years ago.

Our solar system: the Sun, planets, Earth, Moon, and asteroids formed from the remnants of this material.